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Úrsula Oswald Spring
Editor

Water Resources in Mexico

Scarcity, Degradation, Stress, Conflicts, Management, and Policy

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Water Resources in Mexico

Scarcity, Degradation, Stress, Conflicts, Management, and Policy

With 196 Figures and 74 Tables

Springer

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The top photograph illustrates the impact of a flood in Tabasco; the lower-left photograph shows campesinos planting onions in El Pañuelo and the lower-right photograph a water ceremony in El Texcal, both in the state of Morelos in Mexico. All photographs were taken by Úrsula Oswald Spring, who also holds the copyright.

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The professional translation was done by Dr. Serena Eréndira Serrano Oswald. As a native English speaker, Mr. Mike Headon of North Wales (United Kingdom) carried out the style correction of the copy-edited text. Finally, the layout was produced by Mr. Thomas Bast (AFES-PRESS, Germany), the production editor of the Hexagon Book Series. Within Springer Publishers the editor would like to thank Dr. Christian Witschel, the editorial director of Geosciences in Heidelberg, and Ms. Almas Schimmel who prepared the book for publication within the publishing house. Thanks to the expertise and devotion of all these persons this book was made possible.

Lastly, it is important to highlight that this is the first collective work that presents the state of the art of water research in Mexico to a global audience. It reflects the first steps towards a complex, interdisciplinary, inter-institutional and international understanding of water-related issues. It also includes many concrete proposals for improving water management policy globally. It is hoped that these positive suggestions and constructive critiques will help Mexico to move gradually towards a better environmental, social, political and culturally sustainable water management that will generate well-being, enhance the quality of life, reduce the number of water-related conflicts and thus contribute to water-peace for all inhabitants of this beautiful country.

Cuernavaca, Morelos, 10 April 2011 Úrsula Oswald Spring, editor

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- *Figure* 2.2: Spatial distribution of annual precipitation. *Source*: CONAGUA (2008b).
- *Figure* 2.4: Regional contrast in terms of development and water availability. *Source*: CONAGUA (2008).
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- *Figure* 2.13: Aquifers currently affected by sea water intrusion. *Source*: CONAGUA (2008b).
- *Figure* 2.14: Biochemical oxygen demand in Mexico, 2007. *Source*: CONAGUA (2008b).
- *Figure* 2.15: Over-exploited aquifers by hydrological and administrative region. *Source*: CONAGUA (2008c).

Some figures are based on previous publications by *Felipe I. Arreguín Cortés* and co-authors, for which they hold the copyright:

- *Figure* 2.3: Water balance of Mexico. *Source*: Arreguín et al. (2007).
- *Figure* 2.10: Behaviour of maximum temperature in Mexico, 1961-2040. *Source*: Arreguín, Chávez, and Rosengaus (2008).
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- *Figure* 2.12: Currently over-exploited aquifers where an increase of temperature and a decrease of rainfall is expected in the year 2040. *Source*: Arreguín, Chávez, and Rosengaus (2008).
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- *Figure* 2.17: Amount of net virtual water imported into Mexico (2000-2007). *Source*: Arreguín et al. (2009).

The following figures are based on publications by US agencies that are in the public domain:

- *Figure* 2.8: Increase of carbon dioxide concentration in the atmosphere and global rise of temperature in the past thousand years. *Source*: Oak Ridge National Laboratory, at: <http://cdiac.esd.ornl.gov/trends/temp/jonescru/jones.html> (based on Johnes/Mann, 2004 for the years 1000-1880, and for the years 1820 to 2005 on Johns/Parker/Osborn/Briffa, 2005).
- *Figure* 2.18: Soil moisture for May 2009 (in mm). *Source*: CPC and NOAA (2009); at: <http://www.cpc.ncep.noaa.gov/soilmst/leaky glb.htm>.

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- *Figure* 2.9: Sealevel variation (period 1883-2004). *Source*: Modified and extended by the authors based on Douglas (1997).

In chapter 3 *Ignacio Sánchez Cohen, Úrsula Oswald Spring, Gabriel Díaz Padilla,* and *José Luís González Barrios* developed figures 3.1 to 3.4. Some figures are based on previous publications by *Ignacio Sánchez Cohen* and *Úrsula Oswald Spring* for which they hold the copyright:

- *Figure* 3.3: Conceptual model of the cascade effect stemming from precipitation problems in basin RH36. The grids portray gaps in knowledge. *Sources*: Sánchez (2005: 44); Sánchez et al. (2006: 2, 2007: 13).
- *Figure* 3.5: Structure of an integrated water management model in a basin: dynamic, self-regulated and dissipative system with four subsystems. *Source*: Oswald (2005: 68).
- *Figure* 3.7: Use value and exchange value of water. *Source*: Oswald (2005: 147), modified from Ramos (2004: 101).

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- *Figure* 3.6: Decision-making chart at the basin level. *Source*: CONAGUA (2003: 3).

In chapter 4 *Gabriel Díaz Padilla, Ignacio Sánchez Cohen,* and *Rafael Alberto Guajardo Panes* relied in figures 4.3 to 4.7, 4.8 and 4.9 to 4.16 and in table 4.1 to 4.5 on the results of their research. They also used material from CONAGUA that is in the public domain:

- *Figure* 4.2*:* Display of climatic series in R-ClimDex. *Source:* Research data based on information provided by the National Weather Service and CONAGUA.

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- *Figure* 4.1: Start-up panel of the R-ClimDex 1.0 program. *Source*: Zhang/Yang (2004).

In chapter 5 *Miguel Rangel Medina, Rogelio Monreal Saavedra,* and *Christopher Watts* developed figures 5.6, 5.7, and 5.11 based on their research. Some figures are based on previous publications by *Miguel Rangel Medina* for which he holds the copyright:

- *Figure* 5.3: Left: the location of aquifer zones in the Sonora River basin; shading represents different districts of rural development (DDR). Aquifers in the valley whose recharge is modern and the Coast of Hermosillo (CH) with millennial recharge are sh. Right: the administrative division of the aquifers showing DDR 141 (CH) with direction of regional flows. *Source*: Rangel Medina (2006).
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They also used material from CONAGUA that is in the public domain:

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- *Figure* 5.2: Drought indexes in the Sonora River basin. *Source*: CONAGUA (2007).

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- *Figure* 5.9: Left: satellite image interpretation of the Costa de Hermosillo. Right: topography of the crystalline basement in the Costa de Hermosillo. *Source*: Modified from Monreal et al. (2000).

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- *Table* 5.1: Classification of climate types by average annual precipitation. *Source*: Bull (1991).

In chapter 6 *Eugene Perry, Guadalupe Velazquez Oliman,* and *Niklas Wagner* designed figures 6.1 and 6.2 and compiled tables 6.1 based on their research as well as on photos taken by them (figures 6.4, 6.5). Some figures are based on previous publications by *Eugene Perry* for which he holds the copyright:

- *Figure* 6.3*:* Sulphate *vs*. chloride concentration. *Source:* Research data. Vertical axis is 1000[(Sr)/(Cl)]. Horizontal axis is 1/(Sr). Both axes are in units of millimoles/kg. On this plot, mixtures of two waters plot along a straight line. Labels as in figure 6.2. In addition, diamonds are samples from Yucatan state and northern Quintana Roo (taken from Perry et al., 2009).

In chapter 7 *Jaime Garatuza Payán, Julio Cesar Rodríguez,* and *Christopher J. Watts* compiled tables 7.1 and designed figures 7.2, 7.4, and 7.5 based on their research. The following documents do not require permission as they contain research results of the authors:

- *Figure* 7.1: a) Real colour composite and b) evapotranspiration (W m^{-2}) for wheat in the Yaqui valley, Mexico for one day during the growing season of 2000**.** *Source*: Landsat bands 1, 2 and 3.
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In chapter 8 *Felipe Omar Tapia Silva* designed figure 8.4 based on his research. One figure is based on previous publications by *the author* for which he holds the copyright:

- *Figure* 8.3*:* Deforestation rate between 1990 and 2000 for large hydrological basins in south-east Mexico, obtained from LANDSAT images. Left: Grijalva; Right: Usumacinta. *Source:* Tapia-Silva et al. (2007a).
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He used the following material that is in the public domain:

- *Figure* 8.6: Principal screen of a geomatic artefact on the web (under development). *Source*: Mexican Geographic Information System of Water Basins; at: <http://xsei.centrogeo.org.mx/ine/>.
- *Figure* 8.7: Screen for the Cybercartographic Atlas of Chapala Lake. *Source*: at: <http://mapas.centrogeo.org.mx/website/chapala/chapdegradacion/viewer.htm>.
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- *Figure* 8.2: Left: Aquifer vulnerability to contamination in the Mexico Valley basin. Right: index of sources of contamination for the Mexico City urban sprawl zone. Source: Ramos Leal et al. (2010).

In chapter 9 *Enrique Palacios Vélez* and *Enrique Mejia Saez* designed all 10 figures based on their research.

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- *Table* 10.1: Increase in the irrigated surface in the Valle del Mezquital (1931-1990). *Sources*: Bistráin (1961); Aboites (1997); Peña (1997); CEPAL (1991): statistical annexe.

In chapter 11 *Lyssette E. Muñoz Villers, Miguel Equihua, Conrado Tobón,* and *Francisco J. Gutiérrez Mendieta* compiled tables 11.1 to 11.3 based on their research. Three figures are based on previous publications by *Lyssette E. Muñoz Villers* for which she holds the copyright:
- *Figure* 11.1: The Study Area. *Source*: Muñoz Villers/López-Blanco, 2007. Ancillary data from INEGI (1993; Scale 1: 250,000).
- *Figure* 11.2: Monthly rainfall and streamflow distribution in the mature and secondary montane cloud forests, and (b) in the pasture catchments. *Source*: Muñoz Villers (2008).
- *Figure* 11.3: Run-off event coefficient values (*RC*) for each studied catchment. *Source*: Muñoz Villers (2008).

In chapter 12 *José Luis González Barrios, Jean-Pierre Vandervaere, Luc Descroix, Ignacio Sánchez Cohen, Eduardo Chávez Ramírez,* and *Guillermo González Cervantes* designed the four figures 12.1 and 12.8 to 12.10 and compiled three tables 12.1, 12.2, and 12.3 based on their research. They further contributed four photographs (figures 12.4 to 12.7). One figure is in the public domain:
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- *Figure* 12.3: Suction Disc Infiltrometer. *Source*: Vandervaere (1995).

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- *Figure* 13.1: Nazas River basin. *Source*: Adapted from Decroix et al. (2004).

In chapter 14 *Juana Enriqueta Cortés Muñoz* and *César Guillermo Calderón Mólgora* designed figures 14.3 and 14.5 and compiled tables 14.1 to 14.6 based on their research. One figure is in the public domain:
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- *Figure* 15.3: Study area with sampling points. *Source*: Hansen et al. (2010).
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- *Figure* 15.2: North America and MDN Sites. Blue symbols: active sites; white symbols: inactive sites. *Source*: NADP (2009).

One figure is based on a master thesis that was guided by the author:

- *Figure* 15.4: Arcediano Dam River Basin. *Source*: Corzo Juárez (2009).

In chapter 16 written by *Francisco Javier Avelar González, Elsa Marcela Ramírez López, Ma. Consolación Martínez Saldaña, Alma Lilián Guerrero Barrera, Fernando Jaramillo Juárez,* and *José Luís Reyes Sánchez* table 16.1 is based on the authors' research.

In chapter 18 *Julia Pacheco Avila, Armando Cabrera Sansores, Manuel Barcelo Quintal, Ligia Alcocer Can,* and *Mercy Pacheco Perera* drafted figures 18.1 to 18.6 and compiled tables 18.1 to 18.5 based on their research.

In chapter 19 *Catherine Mathuriau, Norman Mercado-Silva, John Lyons,* and *Luis Manuel Martínez-Rivera* compiled figures 19.1, 19.2, and 19.3 and compiled table 19.1 based on their research.

In chapter 20, *Salvador Israel de la Garza González* and *Raúl Herrera Mendoza* compiled all figures 20.1 to 20.13 based on their research.

In chapter 21 *Ramiro Vallejo Rodríguez* and *Alberto López López* compiled table 21.1 based on their research. Three tables were adapted from the copyrighted material based on their research results:

- *Table* 21.2: Methods of analysis used by various authors for the identification of EDCs and ECs. *Source*: Adapted from Yu Zirui (2007).
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- *Table* 21.4: AOP-O3 applied to different types of water and under different conditions. *Source*: Adapted from Esplugas et al. (2007).

In chapter 22 *Linda González* and *Eleazar Escamilla Silva* drafted figures 22.1 to 22.14 and compiled all tables 22.1 to 22.7 based on their research.

In chapter 23, *Úrsula Oswald Spring* drafted figure 23.1 based on her research and on previous publications for which she holds the copyright:

- *Figure* 23.4: Interrelationship between water supply, human demand, and potential conflicts. *Source*: Oswald Spring/Davis Mazlum, in: Davis Mazlum (2004: 17).

- *Figure* 23.10: Hydrodiplomacy. Source: Author's elaboration based on Oswald Spring/ Davis Mazlum *in* Davis Mazlum (2004: 19).
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- *Figure* 23.3: Annual Rainfall in Mexico. Source: CONAGUA (2009).
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- *Figure* 24.1: Location of the twelve water flow measuring points. *Source*: Authors' elaboration using Geographical Information System (GIS) data; at: <http://gisdata.usgs.gov/website/ibwc/viewer.htm>.

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The following four figures were done by former students of the author under her supervision:

- *Figure* 25.5: Topography. Source: Morón Vázquez (2004: 34).
- *Figure* 25.6: Fortnightly histograms. Rain distribution. Source: Ulloa Juárez (2005: 41).
- *Figure* 25.7: Soil distribution. Source: Pérez Hernández (2006: 58).
- *Figure* 25.8: Potential erosion. Source: Pérez Hernández (2006: 62).

In chapter 26 *Claudia Rocío González Pérez* and *Antonina Galván Fernández* drafted figure 26.1 and compiled table 26.1 based on their research. For the following figure permission was granted by the copyright holder:

- *Figure* 26.2: Cycle of knowledge management. *Source*: Solis and López (2000).

In chapter 28 *Jorge A. Morales Novelo* and *Lilia Rodríguez Tapia* developed several figures and tables based on data from SEMARNAT that are in the public domain:

- *Figure* 28.1: Water stress in the Valley of Mexico (2004). *Source*: Prepared by the authors based on data from SEMARNAT (2005: 37).
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In chapter 29 *Arsenio Ernesto González Reynoso* and *Itzkuauhtli Zamora Saenz* drafted figures 29.3 and 29.4 based on their research. The remaining two figures are based on an official government plan that is in the public domain:

- *Figure* 29.1: Location of the Magdalena River basin. *Source*: Master Plan of Integral Sustainable Management of the Magdalena River Basin in Mexico City (SMA-GDF, UNAM, 2008: 9).
- *Figure* 29.2: The planning area of the Magdalena River Master Plan. *Source*: Master Plan of an Integral Sustainable Management of the Magdalena River Basin in Mexico City (SMA-GDF, UNAM, 2008: 16).

In chapter 30 *Alejandra Martín Domínguez, Víctor Javier Bourguett Ortiz, Flor Virginia Cruz Gutiérrez, Miguel Ángel Mejía González, Víctor Hugo Alcocer Yamanaka, Juan Maldonado Silvestre, Gustavo Armando Ortíz Rendón, Petronilo Cortés Mejía, Arturo González Herrera, Martín Piña Soberanis, Ma. de Lourdes Rivera Huerta, Leticia Montellano Palacios, Carlos Eduardo Mariano Romero, and Velitchko Georguiev Tzatchkov* drafted figures 30.1, 30.3, and 30.4, contributed one photograph (figure 30.2), and compiled tables 30.1 to 30.3 based on their work.

In chapter 31 *Rosario Pérez Espejo* designed one figure (31.1) and compiled tables 31.1 to 31.4 based on official government publications that are in the public domain:

- *Figure* 31.1: Location of the state of Guanajuato, Mexico. *Source*: Developed by author, based on INEGI (2009), "Información geográfica".

- *Table* 31.1: Percentage distribution of monitoring stations for surface water quality according to category (BOD, COD, and TSS, 2006). *Source*: Water Statistics (Semarnat-CONAGUA, 2007).
- Table 31.2: Percent of monitoring stations of surface water resources by administrative region using the BOD5 category, 2003. Source: CONAGUA, Management, Sanitation, and Water Quality Department (2005).
- Table 31.3: Irrigation district 011 High Lerma River. Registered users and area by module and total. Source: CONAGUA Agency, state of Guanajuato (2008).
- Table 31.4: Cultivated land, production value, and water use. Source: Research data, survey, based on the Papiit Project (IN 305107).
- *Figure* 31.2: Irrigation District 011 (IR 011). *Source*: Comisión Nacional del Agua-Instituto Nacional de Estadística y Geografía (CONAGUA-INEGI, consulted in 2008).

In chapter 32 *Nicolás Pineda Pablos* and *Alejandro Salazar Adams* compiled tables 32.1 and 32.2 based on their research, and adapted two figures that are in the public domain:

- *Figure* 32.1: Vicious circle of water services. Source: Elaborated by the authors based on: Mario O. Buenfil et al. (2003).
- *Figure* 32.2: Virtuous circle of water services. Source: Elaboration by the authors based on: Mario O. Buenfil et al. (2003).

In chapter 33 *Judith Domínguez Serrano* drafted figures 33.1, 33.3, and 33.4 and tables 33.1, 33.5, and 33.6 based on her research. Several figures and tables are based on official studies that are in the public domain:

- *Figure* 33.2: Hydrological Administrative Region X for the Central Gulf. *Source*: CONAGUA management, Region X (2000 and 2002).
- *Figure* 33.5: Potable Water Coverage. *Source*: State of Veracruz (2005, 2005a).
- *Table* 33.2: Projection for drinking water, drainage and sewerage for rural localities. *Source*: State Water Commission of the State of Veracruz.
- *Table* 33.3: Projection for potable water, drainage and sewerage for urban localities. *Source*: State Water Commission of Veracruz State.
- *Table* 33.4: Supply of water and collection of payment. *Source*: State Water Commission of Veracruz State.

In chapter 34 *Úrsula Oswald Spring* designed figure 34.2, used figure 34.1 from a previous co-authored brochure, and compiled table 34.1 from data from CONAGUA that are in the public domain:

- *Figure* 34.1*:* Complex interrelations within the 'environmental quartet'. *Source:* Brauch and Oswald Spring (2009: 12).
- *Table* 34.1: Water volume in million m^3. *Source*: CONAGUA (2008).

Preface

Estela Morales Campos

In our time, debates and proposals surrounding water research and water resources have attained an unprecedented importance. There has been increasing generation and propagation of ideas and knowledge, as well as of projects aimed at solving current worldwide water challenges; our country has not been the exception. In Mexico, various institutional programs have flourished, centred on aspects such as: the development of water use and reuse capabilities; systematizing public knowledge regarding water management; subsistence and recovering ecosystems closely tied to water uses and administration.

The National Autonomous University of Mexico, for example, has promoted the UNAM Water Network (RAUNAM) among its recent projects. This specialized network emerged in the context of the IV World Water Forum that took place at the beginning of 2006 in Mexico as a response to the complex problematic exposed in the Forum by the academic community. Today, RAUNAM constitutes an active and effective partnership platform enabling members of the university to keep up to date regarding research, taught courses, and other water-related activities.

Equally valuable has been the constitution and consolidation of the Scientific Network on Water (RETAC) by the National Council on Science and Technology (CONACYT). RETAC is part of CONACYT's efforts to integrate the sum of contributions by institutions, researchers, and academics, as well as by civil organisations and businesses. It was created in January 2009 following a multi-institutional meeting in order to face the scientific, political, social, cultural, and business challenges of water in Mexico, and to contribute to a sustainable management and equitable and responsible administration of this indispensable natural resource. Fundamentally, RETAC is oriented towards: a) understanding the complexity of water-related problems; b) developing new technologies and research methods; c) homogenizing scientific research methods for comparative purposes; d) reflecting about hydrological policies in order to protect Mexico from the impact of climate change; and e) disseminating findings.

Resulting from the discussions of the first RETAC's international congress in 2009, the collective work *Water Resources in Mexico. Scarcity – Degradation – Stress – Conflicts – Management and Policy* is here presented. Its multidisciplinary and multi-institutional character is one of its most distinctive features, successfully gathering the reflections, doubts, analyses, and viewpoints of scientists, specialists, public servants, and entrepreneurs from different disciplines and sectors. In addition, the fact that each chapter has been blindly peer-reviewed gives the book academic and institutional integrity.

The book is divided into five sections. Following the rich and detailed introduction by Úrsula Oswald Spring and Ignacio Sánchez Cohen, part I "Hydrological processes and management of basins" examines systemic aspects linked to water management in our country. It accounts for the way in which work by researchers has configured and validated algorithms to quantify water quality and availability in each of its uses. Without minimizing the problems presented by climate change and environmental degradation, the approach in this section highlights the need to incorporate case studies in order to propose similar behaviour patterns in distinct regions of the country and to find possible solutions to this complexity.

Taking into account that the agricultural sector is the main beneficiary of national water reserves, with irrigation units and districts mainly located in arid and semi-arid regions, part II "Water use, availability, and alternative sources" explores distinct facets of water use, including water quality measurements and estimations, contamination processes, use and reuse of treated wastewaters, and human consumption. Irrigation engineering is also considered, including water supply for agriculture, aiming at greater global efficiency in order to strategically deliver water to both developed and developing regions.

Part III, "Water quality, pollution, and health", addressing this linked group of issues, includes work surrounding the disturbing problems relating to the pollution of surface and groundwater bodies caused by natural and anthropogenic factors. Collaborative researchers present calculations and deductions concerning the processes of contamination at the same time as exploring legal and normative aspects – a domain where our country often lacks effective law-enforcement mechanisms and efficient regulations, leading to terrible sanitary damage.

Part IV, "Social effects, conflicts, and hydrodiplomacy", takes the interrelation between the alarming pace of climate change and water scarcity in some of the country's regions as starting point. Scarcity is exacerbated by rapid demographic growth, and by increasing water demand in the agricultural, industrial, and domestic use sectors. Among other topics, the section tackles issues such as water conflict prevention and hydrodiplomacy; concepts such as water security (and its relation to food and health security); border economics and its impact on hydrological resources; the need for a sustainable culture in the face of complex hydrometeorological emergencies, etc. In sum, the section presents solution-based research, seeking to extend the benefits of quality water resources for all.

"Public policy, economy of water, institutions, and legal aspects" constitutes the fifth and last section. It is fundamental for investigating solutions to all the different water-related problems. Authors examine the history of the public policies of various institutions in order to envisage agreements that include citizens' involvement. Crucial topics are dealt with, including diffuse agricultural pollution and point discharges, as well as the quest for an integral management within existing norms and laws that will take into account demographic growth and the changes our planet is undergoing. The importance of organizing all the actions that contribute towards an improved water use has led to the conclusion that responsibility for water use should be societal, leading to the outlining of a common project.

In synthesis, *Water Resources in Mexico. Scarcity – Degradation – Stress – Conflicts – Management and Policy* encompasses definitions, deficiencies, expectations, observations, and critical thinking surrounding water research in Mexico. As a result of its first years of work, CONACYT's Scientific Network on Water presents an interdisciplinary, inter-institutional, and inter-sectorial analysis of the state of the art of water and water-related topics, at the same time as putting forward a variety of aspects calling for further research in the immediate future.

Water constitutes a great responsibility for us all. Collective participation in order to solve the problems derived from its scarcity, quality, use, management, and pollution is both urgent and essential. Works such as this represent an invaluable effort to raise awareness of a current phenomenon that is permanently subject to change, demonstrating the urgency of continuing to work on solutions for the common good.

Introduction

1 Water Resources in Mexico: A Conceptual Introduction

Úrsula Oswald Spring and Ignacio Sánchez Cohen

1.1 Introduction

Water use and management is of crucial importance for everyday life and also for productive processes, as well as for the conservation and recovery of ecosystems. In only two decades (1990–2010), water consumption on the planet has doubled. In Mexico, due to population growth and agricultural and industrial production, water availability per person has become increasingly limited. This shrinking water availability is partly a consequence of the geo-ecological distribution of the population given that 58 per cent of its national territory has drylands – semi-arid, arid and hyper-arid (desert) ecosystems – that are below the average national rainfall. Due to climatic uncertainty all processes of planning for human demand and for production requirements are highly uncertain. Furthermore, it is precisely in these drylands that the main irrigation districts are located, that 70 per cent of the Gross Domestic Product (GDP) in the agricultural sector is generated, and that 92 per cent of the irrigated lands are located, with an overall efficiency of water use of below 40 per cent. Agriculture consumes most of Mexico's water reserves (77 per cent), followed by domestic consumption with 13 per cent and industrial use with 10 per cent (CONAGUA, 2009).

The second problem for water availability in Mexico is that of periodic variations, as most rainfall occurs during the rainy season between June and October, compared with the rest of the year which is characterized by a dry season that forces peasants and agribusinesses to use water from dams, rivers and aquifers. The wide variability of the spatial and temporal distribution of rainfall has increasingly been influenced by an anthropogenically-induced *climate change* (CC; UNFCCC), something that has made equitable water management more difficult. Therefore, it is necessary to develop technologies that increase productivity per water drop, as well as to promote a culture of water saving, especially for agricultural, industrial and domestic activities. As water can be reused in households and for agriculture, this contributes to the challenge of developing efficient water treatment processes and the reuse of treated water.

1.2 Objectives

The complexity of water management encompasses the varied uses and reuses of water, including human, productive, agricultural and environmental factors. The objective of this book is to develop an interdisciplinary, inter-institutional and inter-sectorial diagnosis of research, institutions and infrastructure relating to water in Mexico. The *Scientific Network of Water* (RETAC) of the *National Council on Science and Technology* (CONACYT) addresses many new scientific, political, social, cultural and business challenges. Its goal is to contribute to a more sustainable administration of water, and to a more responsible and equitable water management policy. RETAC is also responding to a novel scientific policy within CONACYT, where synergies are being created between researchers, institutions, social movements, civil organizations and enterprises in order to solve complex water issues in a collective and peaceful manner. The distinctive feature of this effort is its multidisciplinary and multi-institutional outlook, featuring studies with multiple objectives in order to integrate areas of expertise and methodologies to solve complex contemporary problems relating to water.

Mexico has already been severely affected by climate change and large parts of its territory are covered by arid lands, where water availability is limited due to temporal and regional factors that are linked to the rainy season. Given these complex challenges, researchers from different disciplines have converged in order to engage in an open and honest dialogue guided by common interests so as to learn from their respective viewpoints, techniques and analytical tools. Integrating businessmen and public servants into this dialogue opens the possibility of suggesting alternatives, of offering sincere critiques of water policies, of devising strategies for mitigating the effects of more

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severe droughts and extreme hydro-meteorological events, and of contributing to processes of adaptation for coping with global climate change. In the social domain, the book provides many resources to stimulate groups to organize themselves and to improve their capacities for resilience, with the goal of protecting themselves against new and unknown risks, thus reducing their environmental and social vulnerability.

This book is the result of a systematic review by a group of water specialists who are active not only in many academic fields, but also as public servants and entrepreneurs. All chapters were anonymously peer-reviewed by at least three and up to five experts. The authors whose papers were accepted for publication incorporated the many suggestions of the peer-reviewers and revised their texts accordingly.

RETAC, the results of whose work during the first two years are presented in this book, aims to better understand the complex problems relating to water by developing new technologies and analytical tools, by homogenizing scientific methods to enable comparisons, by reflecting on water policies in Mexico in the face of climate change and by disseminating scientific results to governments and businesses with the goal of implementing them in safe water and sanitation systems, in agricultural and industrial processes, in the conservation of aquifers and surface water resources, as well as in the preservation and recovery of ecosystems.

During its first national meeting from 21 to 23 January 2009 at the Ex-Hacienda of Cocoyoc in the state of Morelos, various sectors were represented including researchers, institutions, federal, state and municipal water management authorities, civil servants in charge of drinking water and sanitation, entrepreneurs, and members of civil society. Following a meticulous analysis of the complex interrelations between social and environmental factors related to water, the discussions assessed gaps in knowledge and deficits in existing public policies. This led to the development of certain general thematic areas and their current shortcomings that organized research and public policies should address. This included problems such as the lack of an integrated socio-environmental approach, deficits in water administration and management, or where partial and short-term interests prevail over general interests and processes, thus leading to negative outcomes in the middle and long term.

A clear example of this is that over-exploitation of aquifers has occurred in dry areas, where intense pumping at great depths has generated subsidence, intrusion by sea and brackish water, pollution by metals that imperil human and environmental health, and most importantly, encumbrance of water supply for productive and domestic processes. Given the complexity of the topics that have been addressed, the authors have tried to pave the way towards an unknown yet promising path. The authors hope the reader will also join in this effort by enriching this work with additional reflections that should not only focus on the water situation in Mexico, but also be useful for other countries facing similar problems.

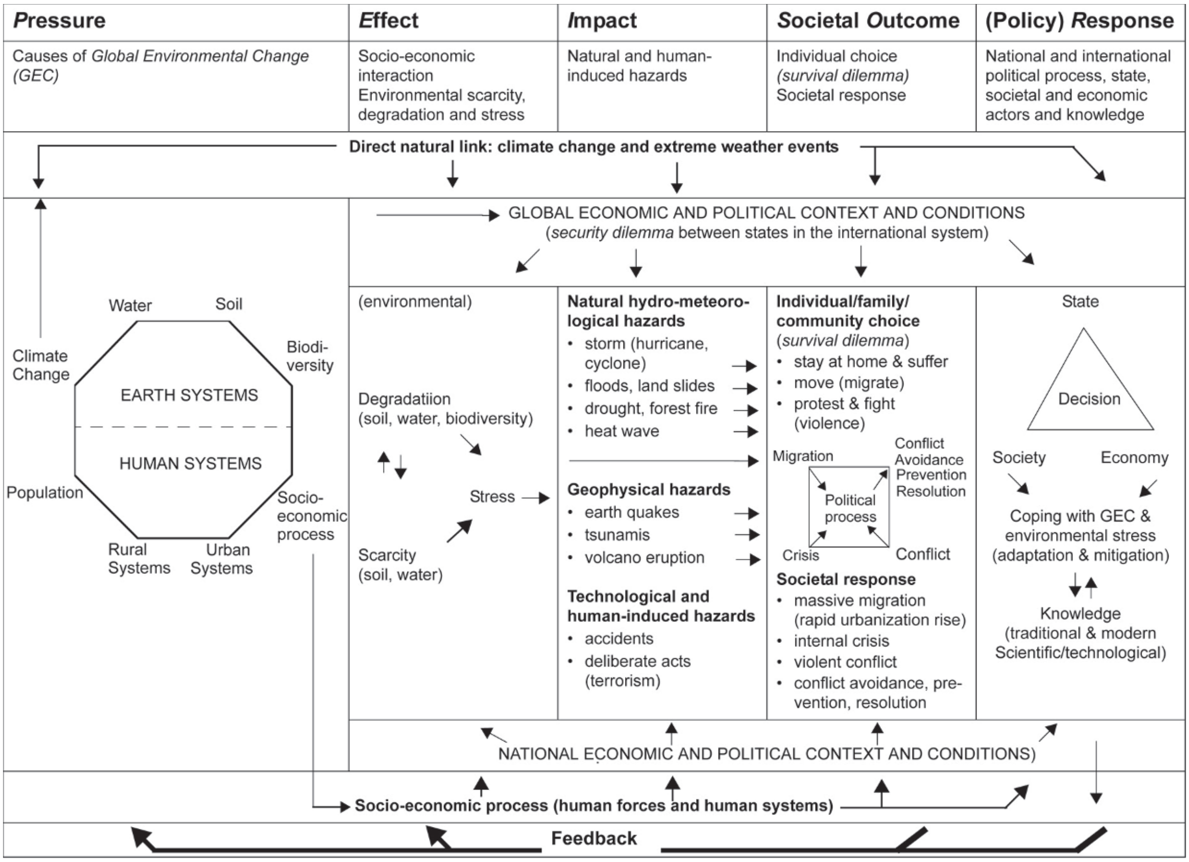
1.3 Some Conceptual Reflections

Climate change and more extreme hydro-meteorological events will have consequences for drylands and they will result in changes to agricultural demand and to productive processes. Water-saving systems and the higher efficiency of drop-by-drop irrigation in food production require adequate technologies such as mulching, micro-irrigation tunnels, bio-fertilizers, reuse of agricultural by-products, sensors to measure soil humidity, and the development of efficient irrigation plans according to specific crop needs. Nevertheless, the existing waste of water in agriculture, the lack of trust in government activities, the corruption and the attitudes of traditional producers limit the use and promotion of such technologies, thus impacting adversely on the quality of life of producers, and accounting for both technological and social gaps.

Integrated water management means transforming the current remedial 'end-of-pipe' sanitation policies by actions geared to prevent pollution and to foster clean production processes. The prevailing chaotic urban development and the lack of sustainable rural policies urgently require territorial planning with comprehensive environmental management that involves all actors to their mutual benefit. Financial and legal mechanisms to quantify environmental services are also necessary. Environmental services are usually provided by people living in the upper basin who often represent the poorest groups in Mexico.

The analytical goal is a complex study of providing a transverse diagnosis of water research that can translate into just and sustainable public policies. This book constitutes a first step in this direction, linking different disciplines to begin weaving a fine set of interrelations. This also implies combining the different levels of analysis to prevent the fallacy of the equivocal level. To better understand the interdisciplinary complexity and the dynamic of global environmental

Figure 1.1: PEISOR Model. **Source:** Brauch and Oswald Spring (2009: 9).



changes, particularly of climate change, the PEISOR model[1] was gradually developed (figure 1.1). It consists of five elements:

P: *Pressure* including the interaction among at least eight socio-environmental factors constituting global environmental change;

E: *Effects* of the relationship between scarcity, environmental degradation and environmental stress;

I: *Impacts* of extreme hydro-meteorological events that turn into disasters due to human activities;

SO: *Social consequences* such as hunger, forced migration, shanty towns, environmental conflicts, resource wars and failed states;

R: *Policy Response* by actors and institutions involved and affected while facing the dynamic processes of global environmental change.

Pressure links the four natural factors (air, water, soil and biodiversity) with the four human processes (demographic growth, rural systems, urban systems and productive socio-economic processes). As part of the *Earth System*, the air is affected by an intensive burning of hydrocarbons since the start of the industrial revolution, which has been the primary cause of anthropogenic climate change. Reduced precipitation rates combined with torrential rains have eroded soils and thus contributed to desertification. Water scarcity, temporary floods, soil fertility loss and desertification also constrain biodiversity. This destructive impact of the *Human System* on the *Earth System* has resulted in air pollution, in extreme temperatures,

1 The PEISOR model evolved gradually, stimulated by various stimulus-response models that have been used over the years by OECD, the UNCSD and the European Environment Agency (Brauch, 2005, 2009). It addresses the complex interactions between natural and social factors, taking existing global and specific national socio-economic and political conditions into account. The present version of the PEISOR model was first presented at a Special Event of the *United Nations Convention to Combat Desertification* (UNCCD) during the 17th Session of the *UN Commission on Sustainable Development* (UNCSD) on 14 May 2009 in New York when a study on soil security was launched written by Hans Günter Brauch and Úrsula Oswald Spring on *Securitizing the Ground, Grounding Security* (2009: 9).

drought, water scarcity and water degradation, multiple forms of soil erosion, destruction of ecosystems and loss of biodiversity. At the same time, social systems due to demographic growth have put pressure on natural resources. Changes in land use and the intensification of socio-productive processes have significantly transformed rural and urban systems. The increasing demand for natural resources (water and food) has caused scarcity, while intensified industrial processes have led to pollution. Both processes have severely affected the Earth as well as the human systems.

The *effects* of this interaction between human and natural systems generate scarcity, degradation and environmental stress. During the 20th century the world's population tripled while the water demand increased sixfold with no increase in efficiency. Besides the increasing demand for food, the increasing use of some foodstuffs for biofuels (e.g. of sugar cane as ethanol, cereals as biodiesel) and a chaotic urbanization have generated many new risks (floods, landslides, soil fertility loss, soil erosion and desertification). This environmental stress puts greater pressure on natural systems, and this has affected social systems as well. The greater the impact of climate change, the greater the damage to water, air, soil and biodiversity. A polluted natural environment reduces the capacity of the ecosystems for resilience, putting pressure on socio-political systems through illness and human losses during disasters, as well as through the high cost of reconstruction.

The *impact* of environmental stress, exacerbated by climate change, has increased the intensity of hydro-meteorological events. While droughts have caused forest fires, wind erosion, sandstorms, more severe cold spills and heatwaves have harmed human health and the ecosystem. At the same time, droughts and hurricanes have caused a deterioration of environmental services, affecting socially vulnerable groups most, especially women and children.

Societal consequences are many, and this has sometimes created a vicious circle. Greater socio-environmental vulnerability affects personal and socio-economic development. Processes of desertification, drought and floods destroy agricultural production and cause deterioration of the means of subsistence of often marginal and poor rural populations. The diminution of water and foodstuffs, due to a loss of the soils' natural fertility, has generated hunger in many countries. When people migrate to improve their life conditions, conflicts over land, water and jobs sometimes develop and escalate. These complex interrelations between environmental and social phenomena have also deepened existing conflicts in Mexico, generating confrontations about the possession of the land or rights to cultivate it, and the use of springs, wells and other water resources. According to data supplied by the Mexican Agrarian Attorney, in 2007 there were approximately 390,000 agrarian conflicts, due to changes to article 27 of the Mexican constitution that allows *ejido*[2] land from 1992 on to be rented, sold and transferred in association with agribusiness. There have similarly been an equal number of water conflicts.

Response refers to the political processes where three core actors interact: the state, the business community and society as a whole. Mitigation and adaptation policies and measures dealing with global environmental change derive from traditional and modern scientific knowledge based on technological and scientific research and innovation. Decisions are the results of negotiation processes, where consensual agreements between the three social sectors respond to the complex interrelationships between natural and social systems. Climate change, the worsening condition of water, soils, biodiversity, changes in urban and rural systems, the intensification of productive processes, and increasing demographic growth rates produce multiple risks for national and international security, as well as for human security. Thus, good governance responds to anticipated learning processes due to an increased awareness of the population regarding both environmental and social threats. It also calls for proactive politics to prevent and reduce negative interactions between environmental and socio-political processes.

The history of Mexico offers an illustrative example. Since the collapse of the Maya civilization – due to an over-exploitation of scarce natural resources in fragile ecosystems that resulted in a series of famines and pandemics, but also due to the genocide of the native populations from the Spanish conquest until Independence (1810) and the Mexican Revolution (1910) – repeated and prolonged periods of severe droughts require a clear understanding of the relationship between natural and socio-political factors (Sánchez Cohen et al. 2011; Blümel, 2009). These past

2 Ejido is the term created for the land that was assigned after the Mexican revolution in 1910 to the peasants who had fought for this land. From 1992 on, President Salinas declared that the land reform had been completed and announced that no more land would be distributed.

experiences should serve as a warning signal for Mexican society as a whole, given the sensitivity of the current socio-environmental and political situation. A severe drought has affected large parts of Mexico from 1994 to 2010. Since 2005, an increasing number of hurricanes of greater severity have occurred, as well as floods and a deepening poverty among rural populations, which has forced many affected people to emigrate to the USA (Oswald Spring 2011). The tightening of controls along the border between Mexico and the United States and also the Anti-immigration Law SB1070 that was adopted in Arizona in 2010 have also resulted in a greater number of Mexicans being deported and jailed, where they had only sought work and better living conditions in the US. This undocumented migration has become increasingly complex due to the involvement of criminal organizations in drug and human trafficking as well as the arms trade, and has resulted in mounting public insecurity.

The diagnosis of these complex interrelationships between natural and human systems using the PEISOR model represents a first step in addressing these problems with a transverse and interdisciplinary approach, to which this book hopes to contribute. The hope is that it will also help overcome the vicious circles of natural resource degradation and the loss of quality of life. In Mexico, risk reduction and long-term food sovereignty is rooted in the dynamic interrelationship between water, soil, reduction of greenhouse gas emissions, sustainable agricultural production, affordable food prices, and the quality of education, as well as subsidies and policies for rural and industrial production and job creation. This would prevent the undesirable social outcomes and forced survival conditions currently reflected in forced environmental migration, public insecurity, violent conflict, hunger and obesity. Undoubtedly, analyzing water management is highly complex and obliges government, society and the business community to negotiate an alternative development model, where sustainable peace prevails, mitigating conflicts through hydrodiplomatic models, and where an integrated and sustainable water culture helps create a less hazardous future in the environmental, social and political realm.

1.4 Organization of the Book

With the aim of contributing to the objectives described above, this book is divided into nine sections. It starts with a preface and after this introduction, part I is devoted to hydrological processes, the management of water basins and the interaction between climate, land and biota. Part II addresses water use and availability, scarcity, and alternative water resources for productive processes. Part III deals with water quality, natural and anthropogenic pollution, and its repercussions for human and environmental health. Different water cleaning technologies are suggested, departing from the hypothesis that changing productive processes to prevent pollution is cheaper and more efficient than treating discharges 'at the other end of the pipe'. Water quality, water availability and water scarcity have so far had important social effects, sometimes resulting in conflicts, but also in negotiation processes that are analysed in part IV.

The field of international relations and issues related to the border extending to more than three thousand kilometres between Mexico and the USA are also addressed, in conjunction with the microsphere of community struggles over the control of rivers, wells or springs. In all these cases, alternative processes of organization and a hydrodiplomatic model are proposed to avoid future conflicts and to solve existing ones peacefully.

Part V includes novel public policies, institutional designs, water economy and legal aspects in order to improve water administration and basin management. Participatory governance demands readjustments to the traditionally authoritarian politics of Mexico, involving a willingness to find new ways on behalf of existing interests and some insensible authorities responsible for water management at the federal, state, municipal and local level.

In the concluding remarks, the editor offers a balance sheet between new achievements and deficient areas related to water research in Mexico. This book is complemented by a thematic index, the biography of the authors, and a list of abbreviations.

1.4.1 Part I: Hydrological Processes and Basin Management

Part I (chapters 2 to 6) addresses hydrological processes, the management of basins and the interaction between climate, land and biota. It comprises a variety of structural topics related to an integrated management of water for diverse uses where various experts have developed and validated algorithms to quantify water availability and quality. The importance of this topic combines the scientific analysis of different case studies throughout Mexico to identify similar behavioural patterns and cause-effect relations that could be replicated elsewhere. Here, the use of physical methods prevails.

This part starts with chapter 2 by *Felipe Arreguín*, the Deputy Director of the National Water Commission, who was assisted by *Mario López Pérez* and *Humberto Marengo Mogollón*. The authors offer an assessment of the water challenges that Mexico faces in the 21st century. Mexico has a territory of 1.964 million km^2 and an average annual precipitation of 775 mm for a total population in 2010 103.3 million inhabitants, of whom three-quarters live in urban areas. Nevertheless, 77 per cent of water is used for agriculture and ANUR (Asociación Nacional de Usuarios de Riego; National Association of Irrigation Users) is the association representing the farmers who are using water for irrigation in Mexico. This is part of a water balance that relates rainfall and population growth to water use and pollution. The authors offer a critical evaluation of surface and groundwater management. The most important challenge is climate change, as both coasts are threatened by rising sea levels, and higher temperatures will increase regional and temporal water scarcity and degradation.

Using many figures and tables, the authors suggest an integrated water management. They explore alternatives such as the creation of a new infrastructure, water saving, reuse, recycling and water treatment. The National Water Plan (2007–2012) focuses on a vision that integrates all water available and used in Mexico, including 'virtual' water savings through imported crops, as well as water used for agricultural exports, soil humidity, and desalination of salt water. The overall vision is to achieve a water balance where an integrated water management satisfies the demand of present and future generations, accounting for population growth and new social and productive needs.

In chapter 3, *Ignacio Sánchez Cohen, Úrsula Oswald Spring, Gabriel Díaz Padilla* and *José Luís González Barrios* propose an integrated water management model. They take the hydrological basin as the basic planning unit for regional development, where actions that integrate all stakeholders are undertaken including planning related to surrounding tributary rivers and aquifers. The authors include the planning for and organization of a new infrastructure, as well as control over water allocations. They also promote the development of new laws and regulations that deal with the challenges posed by climate change, water scarcity and pollution. Through a multi-institutional and multidisciplinary outlook, they seek to involve decision-makers at different stages of water processes, replacing old authoritarian models of water management.

In chapter 4, *Gabriel Díaz Padilla, Ignacio Sánchez Cohen* and *Rafael Alberto Guajardo Panes* put forward an algorithm for the analysis of rainfall time series for Mexico, using data supplied by the five thousand weather stations distributed throughout its territory. With mathematical and statistical processes as well as interpolation techniques, gaps are estimated and maps are generated based on databases using refined information from atypical registers, making estimates through a climatic generator, assessing the viability of adjusting data and critically evaluating interpolation techniques. The authors observe that the 4.3 version of the ANUSPLIN software developed by Hutchinson (1995) provided the best results for continuous surfaces, followed by the Kriging method, Co-kriging method and finally the inverse of the square distance.

In chapter 5, *Miguel Rangel Medina, Rogelio Monreal Saavedra* and *Christopher Watts* argue that economic growth in the state of Sonora depends on water availability for agricultural production and domestic use. Water supply both in the capital and in agricultural lands depends on groundwater from Mesa de Seri, La Victoria, La Sauceda, and from the coast of Hermosillo. Over-exploitation of the aquifers on the coast of Hermosillo caused by the lack of electric and water tariffs has generated a drop in the static level from 20 to 65 m, leading to saline intrusion from the sea. In order to reverse this trend, it is necessary to balance water costs for domestic and agricultural use, end subsidies, and benefit all inhabitants equitably.

In chapter 6, *Eugène Perry, Guadalupe Velázquez Oliman* and *Niklas Wagner* analyse hydrostratigraphy in the Peninsula of Yucatan. Studying the presence of chloride, sulphate, and strontium ions the authors determine the extent of saline intrusion. Groundwater in and near the valley of the Rio Hondo has high concentrations of sulphate and strontium but unusually low concentrations of chloride. In much of the southern part of Campeche, groundwater ion chemistry is dominated by the dissolution of extensive beds of gypsum/anhydrite-bearing evaporites of probable Palaeogene age that release sulphate and chloride ions to the aquifer. The authors found that given its geo-hydrological composition, surface water may be a suitable source of potable water for communities in the area.

1.4.2 Part II: Water Use, Availability and Alternative Sources

Part II (chapters 7 to 13) of the book deals with water use and water availability and explores alternative water sources. The main beneficiary of available water in Mexico is the agricultural sector, especially for the irrigation districts and units in the arid and semi-arid regions. But water efficiency for irrigation reaches at most 40 per cent. In the management of groundwater a series of poor management practices were detected in a wide range of processes. Surprisingly, the electromechanical efficiency of pumping equipment is extremely low at an average of 28 per cent, which indicates great losses in the process of transforming mechanical energy into hydraulic energy. Throughout this section, researchers deal with the topic of water use guided by very different approaches ranging from methods of remote sensing, to *in situ* water quality evaluation, pollution processes, and water use, treatment and reuse for agricultural purposes and human consumption. Irrigation engineering is a common topic in research linked to the amounts of water used; however, it also addresses questions such as when and how water should be used for crops.

Chapter 7 by *Jaime Garatuza, Julio César Rodríguez* and *Christopher Watts* is the result of ten years' research experience in the north-east of Mexico measuring the evapotranspiration of wheat, cotton, safflower, sorghum, potatoes, beans, chickpeas, chili/pepper, vines and walnuts, using the technique of turbulent correlation and linking crop factors with vegetation indexes determined by satellites with various spectral, temporal and spatial resolutions. Environmental monitoring in the estimation of evapotranspiration allows the establishment of regional water balances and helps optimize irrigation for agriculture. The results suggest the use of meteorological stations and remote sensors, applying them to bigger areas such as irrigation districts.

In chapter 8, *Enrique Palacios Vélez* and *Enrique Mejía Sáez* develop a balance of water uses in Mexico, highlighting the importance of water in agriculture that uses 77 per cent of reserves. The authors discuss the lack of measuring and monitoring schemes, stressing that without precise measurements it is impossible to make sustainable decisions on water and irrigation. They compare cases in different irrigation districts of Mexico where advanced measuring technologies through satellite images have been deployed. Thus, it is possible to know the balance between total areas given to users with concessions and real irrigated land. The results are useful for regulating water concessions in irrigation districts, for learning about groundwater use, and for making the best use and management of this vital liquid.

Felipe Omar Tapia shows in chapter 9 the advantages of using advanced methods of analysis for the study of water. Geomatics is a scientific discipline stemming from the convergence of other disciplines such as *Geographic Information Systems* (GIS), cartography, remote sensing, geodesics and photogrammetry. In common terms, it combines a series of methods for the acquisition, processing, representation, analysis and systematization of knowledge and information with a geographical reference, i.e., where a specific spatial environment is located. The approach is systemic; information is generated by means of remote and geospatial sensors to increase the possibility of finding, analysing and communicating the developments that take place in a specific site. These methods are an important tool for decision-making; they are crucial in order to save important amounts of water in irrigation without negatively impacting on productivity.

For the valley of Mezquital in the state of Hidalgo, *Francisco Peña* analyses in chapter 10 the case of urban wastewater coming from the Valley of Mexico. He distinguishes the quality of water that can be used for irrigation and designs a research agenda. The evaluation of irrigation with wastewater, associated with urban growth and rural development, seems to have collapsed. The author characterizes the parties to the conflict, both for the consolidated cases of irrigation with wastewater as well as for the defenders of clean water for irrigation. Evaluations of public performance are marked by extremely slow sanitation processes, a backlog in execution of public works, and an evident incapacity to implement existing laws. The research agenda links the regional water crises to the failure of national agricultural policies.

Lyssette E. Muñoz Villers, Miguel Equihua Zamora, Conrado de Jesús Tobón Marín and *Francisco Gutiérrez Mendieta* analyse in chapter 11 the hydrological effects caused by the damage of the mesophilic mountain forest. They address how it has been turned into pasture lands and its effects on run-off patterns, temporal, and year-round exports from the high basin of the La Antigua River in the Cofre de Perote-Pico mountain range in Orizaba. Pasture lands produce higher run-off and as a consequence a greater loss of natural soil fertility which in turn decreases productivity. Besides this, the authors show that in regeneration, the forest is able to recuperate its hydrological functionality and generate water flows comparable to those of a mature forest in a relatively short time span.

In chapter 12, *José Luis González Barrios, Ignacio Sánchez Cohen, Eduardo Chávez Ramírez, Guillermo González Cervantes, Jean Pierre Vandervaere and Luc Decroix Jambon* reinforce the hypothesis that groundcover affects hydrological variables. Using the *Suction Disc Infiltrometer* method they study the impact of land-use changes in the surface hydrodynamics of a water receiving basin in the higher Nazas River. The authors quantify water infiltration in well-preserved forest surfaces and compare it to surfaces degraded by deforestation and over-grazing. They argue that changing forest areas into agricultural lands degrades soils in a context where reforestation should prevent deforestation in the hydrological basin instead.

Eduardo Chávez Ramírez, *Guillermo González Cervantes* and *Alejandro López Dzul* in chapter 13 analyse the evapotranspiration in the lower and medium basin of the Nazas River, obtaining important findings for the region. Their work is based on automated capturing of climatic information in order to use it in real-time forecasts for irrigation processes. Their studies have allowed them to get to know the real water demands of crops as walnuts and fodder crops such as alfalfa. With this information it has been possible to plan optimal irrigation times and amounts, congruent with the location in the basin and with weather conditions.

1.4.3 Part III: Water Quality, Pollution and Health

The third part (chapters 14 to 22) deals with water pollution and its repercussions for human and environmental health. The problems derived from water quality are many and some of them are quite alarming. Human health problems derived from the consumption of water of poor quality have been widely documented; nevertheless, today, the main cause of death is polluted water, especially in young infants. Sources of water pollution and their special and temporal variation are the topic of multiple studies across Mexico. Particularly relevant have been anthropogenic factors given that most causes linked to changing water quality have to do with human actions. This is the case observed in national ground and surface water resources, but also in an over-exploitation of aquifers, where dissolved mineral compounds are important limits of water quality standards. Furthermore, polluted water chronically affects the health of users, given that it is often their only water source. In this part, researchers present results linked to geochemical weathering, management of chemical waste, disposal of organic pesticides in agriculture, breaches of the law, and the overall need to establish an efficient official law in this regard.

In chapter 14, *Juana Enriqueta Cortés Muñoz* and *César Guillermo Calderón Mólgora* review a wide range of pathogen microorganisms and chemical polluters that may be present in wastewater and in solid waste. The knowledge of these contaminants (some are regulated and some are known to be emergent) and their impact on water reuse programmes is mixed. When water is recycled as potable water or used to recharge an aquifer via agricultural lands there are four important challenges to bear in mind:

a.) determining the exact concentration of organic compounds, especially emerging or non-regulated ones;
b.) identifying opportunistic and pathogen microorganisms in various taxa;
c.) establishing an efficient and cheap water potabilization treatment system;
d.) preventing possible impacts that post-potabilization residues might have on public health and the environment. The authors suggest a sanitary risk approach in order to determine the various alternatives ways of treating wastewater and reusing it.

Anne M. Hansen and *Carlos Corzo Juárez* summarize in chapter 15 water politics: having enough quality water, recognizing the water's strategic value, efficient water use, protecting water bodies, and guaranteeing sustainable development and environmental conservation (PNH 2007–2012, 2007). They emphasize needs and priorities for evaluating pollution in water basins, with specific reference to Mexican politics, norms and laws regarding water management. The authors insist that there are no programmes to monitor *persistent bioaccumulative toxic substances* (PBTS) and thus there are no inventories or formal evaluations regarding risk and exposure to these substances. Their work puts forward a methodological tool for selecting substances in a PBTS monitoring programme.

Water quality destined for human consumption in the state of Aguascalientes has been severely affected. Thus, *Francisco Javier Avelar, Elsa Marcela Ramírez López, Ma. Consolación Martínez Saldaña, Alma Lilián Guerrero Barrera, Fernando Jaramillo Juárez* and *José Luis Reyes Sánchez* in chapter 16 present the results of the systematic characterization of ground and surface water in Aguascalientes. They correlate the findings of micro-biological and physico-chemical studies of water quality for human consumption with the health problems of the population. They observe various pathologies in exposed populations, including early kidney damage in children.

In chapter 17, *Laura Arreola Mendoza, Luz María del Razo Jiménez, Oliver Barsbier, M. Consolación Martínez Saldaña, Francisco Javier Avelar González, Fernando Jaramillo Juárez* and *José Luis Reyes Sánchez* also find that water destined for human consumption in the State of Aguascalientes contains high levels of lead, cadmium, arsenic, fluorides, and other minerals exceeding limits established by the Mexican Official Standard (NOM) relating to water. Children are an especially vulnerable group, developing chronic renal diseases leading to hospitalization, medical treatment, dialysis and kidney transplants. Given this scenario of health deterioration and renal illness the authors suggest preventive measures to reduce levels of toxic minerals in waters destined for human consumption. In general, this implies reducing the over-exploitation of aquifers and purifying water destined for human consumption, paying particular attention to children.

In the Yucatan Peninsula, *Julia Pacheco Ávila, Armando Cabrera Sansores, Mercy Pacheco Perera, Manuel Barceló Quintal* and *Ligia Alcocer Can* establish in chapter 18 a protocol for measuring cadmium in groundwater. Their conclusions are geared to assessing the efficiency of the model they put forward and the results appear to be reliable. According to their findings, the highest concentrations of cadmium are found in the north-east, the east and the coast of Yucatan. This contamination can be due to agricultural farms or to the use of phosphate fertilizers with high levels of cadmium, as well as to open dumps that contain cadmium residues in porous lands where infiltration is possible.

In chapter 19, *Catherine Mathuriau, Norman Mercado Silva, John Lyons* and *Luis Manuel Martínez Rivera* use fish and macroinvertebrates as bioindicators to assess the quality of aquatic ecosystems in Mexico. They present the state of the art and analyse different perspectives. Their work has focused on studying the structure and composition of aquatic communities in five micro-basins located in the tropical dry forest in the Chamela-Cuixmala biosphere reserve. The authors highlight the importance of pools originating from rainfall in the Chamela basin for the biota. The main findings of this study relate to the description of aquatic communities and the preservation of the conditions best suited for their existence.

Salvador Israel de la Garza González and *Raúl Herrera Mendoza* describe in chapter 20 the types of pollution found in the aquifers of the semi-arid regions in the north-east of Mexico. They map the zones of domestic and industrial pollution, according to the permeability, porosity and depth of the soil. Filtration of hydrocarbons occurs at depths of 2 to 12 metres. They also propose a model of bioremediation of contaminated soils and aquifers in order to bring pollution levels below the limits established by Official Standard NOM-138.

Ramiro Vallejo Rodríguez and *Alberto López López* make in chapter 21 an exhaustive study and present the techniques of identification and analysis of *endocrine disrupting compounds* (EDC) and their degradation through *advanced oxidation processes* (AOP). According to their work, AOP-O_3 promises to be one of the most suitable technologies not only for treating surface water with EDCs such as hormones and chemicals, but also for all kinds of effluents of industrial origin with low biodegradable compounds.

In chapter 22 *Linda González Gutiérrez* and *Eleazar Escamilla Silva* present a study of the biodegradation of a reactive azo red dye from the textile industry in an upflow anaerobic bioreactor with axial dispersion. The results show concentration profiles in the entire reactor and in the bioparticle at distinct concentrations of the dye and at different residence time values; they show a quick saturation and the rapid reaching of equilibrium, and they predict a lower removal when dye concentrations are increased, given that the degradation of the azo dye in this process is abiotic-biotic.

1.4.4 Part IV: Social Effects, Conflicts and Hydrodiplomacy

The fourth part (chapters 23 to 28) of the book addresses the interrelationship between social effects, conflicts, negotiation and strategic planning, in order to augment water availability and deliver quality water for all. For the northern frontier region, complex links between climate change and water scarcity may be observed that are exacerbated by demographic pressure and rising water demand from the agricultural, industrial, service and domestic sectors. Although this region generates a quarter of Mexico's GDP, agriculture consumes 87 per cent of water supply, and it is precisely virtual water exports through the sale of commercial crops that strongly impact on natural and scarce resources, as this is an arid and semi-arid region of Mexico. The coast of Sonora already shows processes of saline intrusion into the aquifers; together with a lack of adequate water and electricity tariffs that reflect real costs and scarcity, this situation will further exacerbate a fragile equilibrium that privileges select groups and might increase existing conflicts. In the central and southern region, new models of integrated water management are proposed, emphasizing social participation. Unfortunately, resistance from the authorities and the interests of a bourgeoisie that is used to over-consumption prevent the emergence of a rational ecological economy that could pave the way for a new water culture. Instead, corruptible authorities and actors with special interests in water resources have led to increasing poverty, scarcity and inequality.

Part IV starts with chapter 23 by *Úrsula Oswald Spring* relating water security and its links to other security concepts such as health and food security. Water scarcity, pollution and a major pressure on water resources have caused an increasing number of water-related conflicts. The author proposes a hydrodiplomacy model where parties in dispute negotiate technical alternatives within an integrated water management process that encompasses all levels, from the household to the basin. Through a peaceful process of conflict negotiation, the parties involved resolve their differences, save water and become actively involved in a water management culture based on human rights and sustainable and rational water use, with the goal of guaranteeing the survival and water governance of everyone, leading to sustainable development.

In chapter 24, *Vicente Germán Soto* and *José Luis Escobedo Sagaz* evaluate information collected by the *International Commission of Limits and Water* (ICLW; CILA in Spanish) about average water flow in twelve measuring points located throughout the Bravo River from 1933 to 2005. Following regression analysis, the authors indicate that both nations have respected international agreements relating to water use. This reflects the fact that variations in water flow correspond with modifications to the agreements, construction of hydraulic infrastructure and times of drought. With this analysis, the authors show that water flows were stable and international agreements have been respected.

In chapter 25, *Antonina Galván Fernández* analyses the productivity of coastal lagoons, which are a product of a mixture of sweet water – from hydrological basins – and salt water from the sea which have gained an entrance because of changing tides. The author studies the basin in the coastal lagoon of Carretas-Pereyra on the coast of Chiapas. These are highly productive areas that generate subsistence and income to the population living on the shore. Also, they constitute natural systems that rapidly degrade due to the silt and low circulation together with non-natural sediments coming from the basin.

Claudia Rocío González Pérez and *Antonina Galván Fernández* develop in chapter 26 a social intervention in order to generate a culture of sustainability and resilience in the face of hydro-meteorological emergencies. Dengue and gastrointestinal illnesses are caused by rising temperatures and changing rainfall patterns. A community in Pijijiapan in Chiapas designed prevention strategies. Also, the community optimized water management, maintenance of the water infrastructure and sanitation of water collection points, and its inhabitants became aware of the importance of keeping water clean. Nevertheless, in order to improve community health, work still needs to be done on productive processes, livestock and pen cleaning, overall sanitation and sanitation of water discharges.

David Barkin documents urban water management research in Mexico in chapter 27. The author highlights the water authorities' incapacity to guarantee an adequate and accessible urban water service, as well as the lack of protection of the ecosystems on which the water supply depends. Also, there is resistance to enabling social participation in terms of water management and oversight of public services, especially in Mexico City. In the theoretical framework of a 'New Water Culture' and an 'Environmental or Sustainable Economy', the author concludes that these problems are part of a strategy to put water in the hands of the elites and of international companies, even if the most pressing social needs are unmet; this generates social conflicts and environmental problems.

Jorge Morales Novelo and *Lilia Rodríguez Tapia* analyse in chapter 28 water scarcity in the *Metropolitan Area of the Valley of Mexico* (MAVM). They conduct a historical review of the evolution and gravity of scarcity, focusing their research not only on water management in the aquifers of the Valley of Mexico, but also on the Lerma and Cutzamala basins. Given current consumption patterns, the capital and its suburban areas will not have enough water to satisfy demand by the year 2025. This calls for a new water policy, based on efficient water use, modifying water consumption patterns, using new technologies, and changing the current water administration rationale and water costs, as well as transforming the prevalent water culture to one where all users participate equally.

1.4.5 Part V: Public Policy, Institutions and Legal Aspects

Part V (chapters 29–33) is dedicated to exploring public policy and existing institutions that deal with water, and to assessing their performance. Past and present legal aspects, together with norms and standards relating to water, have undergone changes due to population growth and a more sustainable management of natural resources. A hierarchical administration with authoritarian elements prevails, hindering civil participation. Thus, this section also contributes to the provision of technical and organizational support to municipal water operating systems. It is the staff of these operating systems who try to comply with regulations and services regardless of the lack of resources, obsolete and dysfunctional facilities, debtors, and pressure by federal and state authorities.

A crucial topic is diffuse agricultural pollution and points of discharge relating to livestock, where a lack of legislation and breaches of existing agreements damage existing resources. Also, in arid and extremely arid zones, water is extracted exclusively from aquifers that are in the process of exhaustion. Existing laws have given priority to surface water, relegating the integrated management of aquifers in their relation to surface water, groundcover, productive processes and contamination. In the face of global climate change, groundwater reserves have become increasingly important. Furthermore, most operating systems in the country are supplied by groundwaters, and it is therefore crucial to work within an integrated management of aquifers, including prevention strategies and a rational price for water use.

New management of water resources calls for new methods of civil participation. Thus, the RETAC team has sought to integrate different actors in a basin management project, where geohydrological, flow and groundcover aspects combine with agricultural, domestic and industrial use factors, especially as rivers have become sewage conduits. Participative processes have been hindered by existing laws and government practices, where special interests have impeded the conservation and recuperation of microbasins and a sustainable use of natural resources. However, budgetary limitations and political timing have also truncated well-designed projects. In order to overcome these limitations, master plans are proposed, designed in such a way as to overcome political timing constraints and to leave projects in the hands of organized civil society. Thus, government and private resources can be linked to resources from citizens and other sources, always within the framework of joint projects. Also, an ongoing monitoring of projects is crucial to avoid mistrust and misunderstandings and to stimulate civil participation. With time, it also limits corruption by protecting scarce resources.

Arsenio Ernesto González Reynoso and *Itzkuauhtli Zamora Sáenz* present in chapter 29 a master plan for the management of the River Magdalena in Mexico City, which includes the restoration and rehabilitation of the basin, environmental and water works, and cultural aspects, as well as the political, social and economic participation of all the actors that live along the basin of the river. Through transverse, interdisciplinary and intersectorial processes, an integrated diagnosis is achieved, conciliating the interests of divergent social classes and designing a flexible and adaptable plan in order to promote public works and generate an environmental culture. However, current participation structures are insufficient given that interests, representation and aspirations force the identification of social actors and entail the need to delimit the space and process as negotiated and not as 'natural'. Also, the rehabilitation of water bodies needs a socially feasible model, where future obstacles are foreseen, and the coordination and cooperation between relevant government offices is guaranteed.

In chapter 30, *Alejandra Martín Domínguez, Víctor Javier Bourguett Ortiz, Flor Virginia Cruz Gutiérrez, Miguel Ángel Mejía González, Juan Maldonado Silvestre, Gustavo Armando Ortíz Rendón, Petronilo Cortés Mejía, Arturo González Herrera, Martín Piña Soberanis, María de Lourdes Rivera Huerta, Leticia Montellano Palacios, Víctor Hugo Alcocer Yamanaka, Carlos Eduardo Mariano Romero* and *Velitchko Georguiev Tzatchkov* evaluate water operating organizations in a valley located in the Central Plateau of Mexico. Through a diagnosis of water supply sources and of water demand, of the operation of purification units, the water quality laboratory, and the commercial and accountable system of the operating organizations, as well as the analysis of alternative sources of water supply for the city and suburban zones, the authors elaborate an action plan that is also useful for other regions in the country. It addresses issues such as poor water availability and poor water quality supply sources, the rapid deterioration of water infrastructure that prevents efficient water extraction, and the outdated tariff system that does not even cover operational costs and limits access to the financial resources necessary for efficient operation of the system.

Rosario Pérez Espejo discusses in chapter 31 problems presented by the design of agro- environmental policies for controlling water pollution. She presents the preliminary results of a study undertaken in Irrigation District 011 in the state of Guanajuato, where the main goal was to collect and analyse information for decision-making. She discusses the role of agriculture in degradation processes from an economic perspective, and reviews the implications of agricultural waste in the politics of different sectors. The author highlights the need to design consensual policies, and to integrate the interests of various stakeholders in irrigation and water resources with environmental concerns to keep a balance between the ecosystem and individual and social well-being.

Nicolás Pineda Pablos and *Alejandro Salazar Adams* analyse in chapter 32 water scarcity in arid and desert zones of the north of Mexico and the southwest of the USA that have been affected by climate change. As population and groups in urban centres increase, appropriate institutions are required to manage water efficiently, thus contributing to the quality of life and to social and environmental sustainability. Existing norms, procedures, and traditional 'uses and customs' limit sustainable water-related behaviour in daily activities, agriculture, livestock and industry. Instead, the authors propose decentralizing levels of autonomy, social participation, assigning responsibilities and self-management, as well as responsible payment, efficient market schemes to determine water quantity and quality *per capita*, and measured volumes of water discharges.

Finally, in chapter 33 *Judith Domínguez Serrano* summarizes a study of the institutional, legal and social changes necessary in Mexico to reach effective water governance after the reform of the *National Water Law* (NWL; LAN in Spanish) in 2004, particularly in the Hydrological and Administrative Region X of the Central Gulf. This area is one of the most polluted regions in Mexico, with important federal funding and yet poor coverage of water services, where the most marginal areas are still lacking potable water and sewage facilities. Besides this, the creation of infrastructure has impeded the development of local capacities and the emergence of responsible authorities and social actors in charge of water management. Even wastewater treatment plants cannot stop pollution as they lack well-trained operators. These old problems relating to water pollution and the lack of infrastructure could be resolved through water governance based on social actors, promoting greater participation, institutional changes and legal reforms.

1.4.6 Concluding Remarks

In her concluding remarks, Úrsula Oswald Spring offers a synthesis of the proposals that were put forward at the First Meeting of the *Scientific Network of Water* (RETAC) in Cocoyoc, Morelos (Mexico) in January 2009. It is noteworthy to see the complex and contradictory – at times even chaotic – interrelationship between the factors of the environmental (air, biodiversity, soil and water) and the social quartets (population growth, rural and urban systems, socio-productive processes). Among the topics that have been insufficiently covered in water research are scant comparative research and methodologies relating to pollution and their repercussions for human health, epidemiological outbreaks and their environmental impacts. The scarcity of surface and groundwater, exacerbated by global climate change, must be assessed in all its details, accounting for health repercussions and environmental degradation as well as for resilience and adaptation mechanisms. Adequate technologies generated in Mexico, an efficient water administration, and socially negotiated water tariffs that cover water management costs and protect the most vulnerable groups could be among the first steps towards a new water culture. Integrating institutions, multidisciplinary research and social participation in water management would create mechanisms to reduce environmental conflicts and guarantee good water quality for all, without generating environmental conflicts or affecting public financial resources. The privatization of water management has been unable to solve the problems of infrastructure and of unequal access to water. Therefore, different norms and laws are necessary to optimize the convergence of public, private and social resources and interests.

Climate change and more severe hydro-meteorological events and their consequences for drylands and agricultural production require changes in productive processes. Systems of water saving and 'every-drop-efficiency' in terms of virtual water require, among other things, the introduction of technological packages such as plastic mulching, micro-irrigation, micro-tunnels, the reuse of agricultural by-products, and the use of biofertilizers and of probes to monitor soil humidity and to identify suitable irrigation times for each crop. Nevertheless, the introduction of these technologies and the subsequent improvement of the quality of life of peasants are hindered by the prevailing culture of producers, characterized by distrust of the government, corruption, and outdated traditional attitudes.

For an integrated water management the transformation of sanitation policies is crucial, especially at the end of the pipe, in order to avoid pollution and to generate clean processes. Chaotic urban development and the abandonment of a sustainable rural politics call for a territorial ordering and an environmental management, benefiting all parties directly involved. It is also necessary to develop legal and financial tools in order to quantify and pay for environmental services generated at all levels of the basin. In order to reach food sovereignty in the future, in a time of mounting uncertainty, it is important to understand the interaction between water, soils, agricultural production, food, prices, subsidies and hunger, in order to prevent complex social emergencies such as high-risk survival conditions, forced environmental migrations, famine, and escalation into violence. Without any doubt, water management is a highly complex issue. It calls for governments, society and businesses to negotiate an integrated development, where sustainable peace prevails (Oswald Spring, 2008; 2005), where conflicts are resolved using models of hydrodiplomacy and of water peace, and where an integrated water culture will lead to a more sustainable and less uncertain future, both in environmental and social terms.

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Part I Hydrological Processes and Management of Basins

2 Mexico's Water Challenges for the 21st Century

Felipe I. Arreguín Cortés, Mario López Pérez and Humberto Marengo Mogollón

2.1 Introduction

2.1.1 Mexico in the World Context

Mexico is the eleventh most populous nation in the world after countries such as China, India and the United States of America; it has the second biggest city after Tokyo, Japan, and it ranks 54th in gross domestic product. In terms of water availability per capita – resulting from dividing overall water resources by the total population – Mexico ranks 89th worldwide, with 4,291 cubic meters per inhabitant per annum. Water abstraction puts the country in 36th place, with an average annual precipitation of 743 m³ per capita.

Weather and topographic conditions have led to the construction of dams to increase the country's water storage capacity, and Mexico occupies 19th place worldwide with a water storage capacity of 150 km³ and 667 big dams. Linked to these structures are irrigation areas, where Mexico ranks 6th, with 6.9 million hectares with irrigation facilities. Finally, the country occupies 90th place for potable water, 67th for the volume of sewage, and 39th for water treatment (CONAGUA, 2008).

2.1.2 Water Balance

Mexico has a land area of 1.964 million km² and a total population estimated at 106.7 million (Villagómez/Bistrain, 2008), of whom 75 per cent live in urban areas. In addition, there are 196,328 villages with less than 2,500 inhabitants (Arreguín, 2005). The average annual precipitation is 775 mm or 1,513 km³, with most rainfall taking place in the period between June and September (figure 2.1). The spatial distribution of rainfall is also uneven, with great differences between the north and south of the country (figure 2.2).

Average evapotranspiration is about 1,084 km³. Aquifers recharge 78 km³, whilst 28 km³ are extracted from them. Average run-off is 400 km³ and surface water extraction reaches 47 km³. The balance in terms of water imports (from the United States of America and Guatemala) is 50 km³ contrasted with exports at 0.44 km³ mainly to the United States of America (figure 2.3).

2.1.3 Water Availability in Mexico

Demographic growth projections up to the year 2030 show that urban areas will grow more than rural areas. If water availability is calculated per capita and per annum in 1950, for each Mexican 17,742 m³ were available compared with the year 2009 when availability declined to 4,261 m³. Estimates predict that for the year 2030 water availability per annum will be 3,783 m³ per inhabitant, taking as a value the yearly average of 458.1 billion m³ into account, which corresponds to the average precipitation from 1950 to 2005.[1]

The distribution of the population in the national territory also creates pressures for water availability. As can be seen in figure 2.4, 77 per cent of the population and 31 per cent of natural water availability is concentrated in the north, centre, and north-east. This also comprises the regions that account for 87 per cent of *gross domestic product* (GDP). This situation in terms of water, population and economics represents an important challenge both in terms of technical and human development.

The problem becomes more complex given that, according to the National Water Law (LAN), the definition of the average water availability of surface water in hydrological basins "is the value that results from the difference between the average volume and

1 The medium availability per capita = the total availability/population. Thus, for the year 2007 the total availability = virgin run off + importation - exportation + recharge = 483,560 m³/year. This availability is considered the same for 2009 and the estimated total population for this year is 113,458,097 inhabitants which gives 4,261 m³/inhabitant/ year.

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_2,

Figure 2.1: Average monthly rainfall in Mexico (1971-2000). **Source:** CONAGUA (2008b).

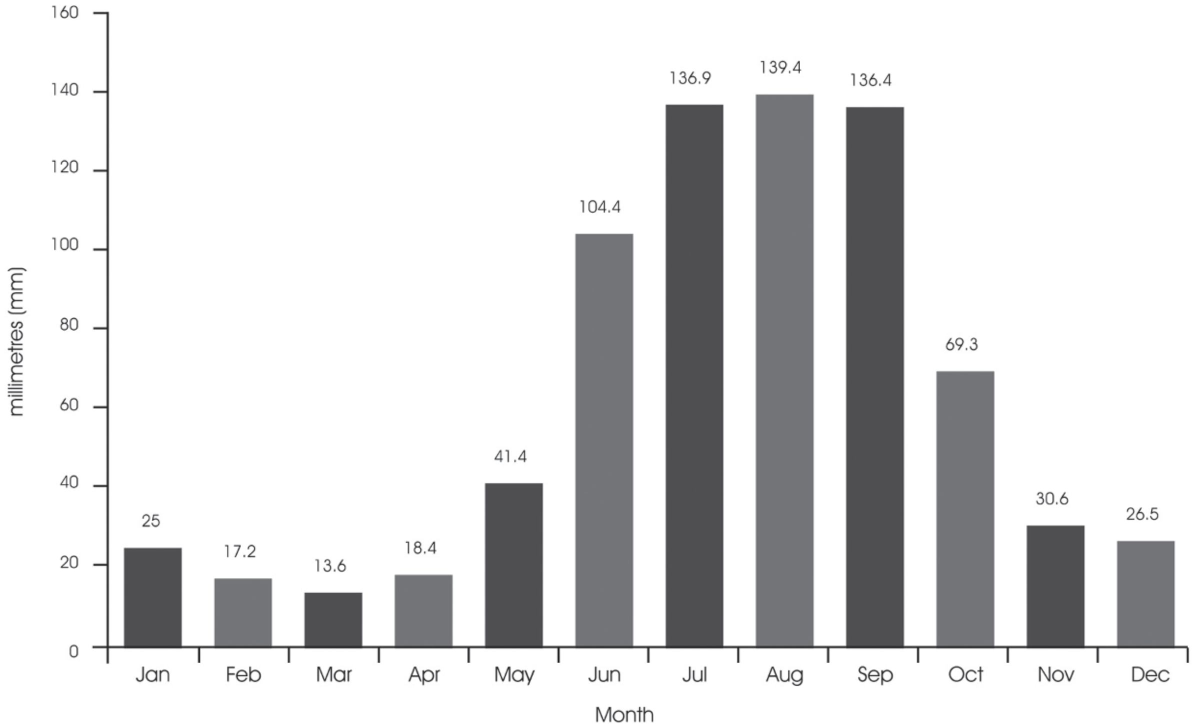


Figure 2.2: Spatial distribution of annual precipitation. **Source:** CONAGUA (2008b).

the actual annual run-off in a basin". This means the legal availability of water for the general population, i.e., the water the general population may use.

Figure 2.3: Water balance of Mexico. **Source:** Arreguín et al. (2007).

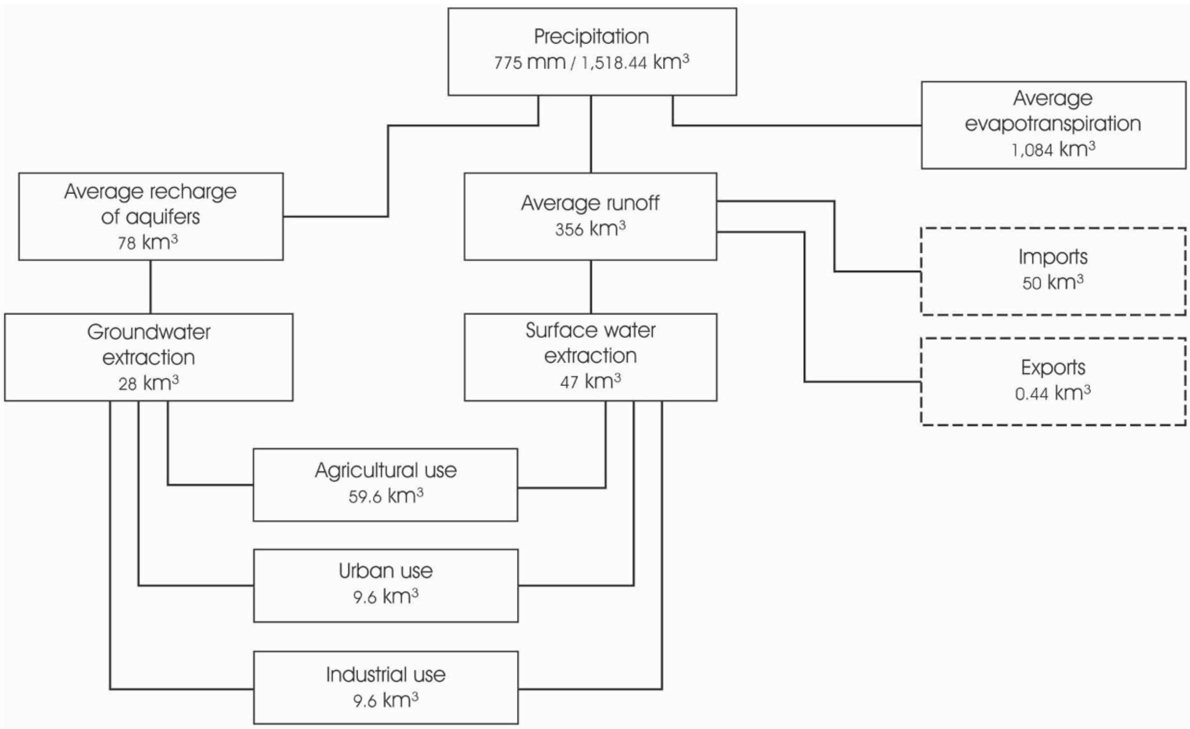
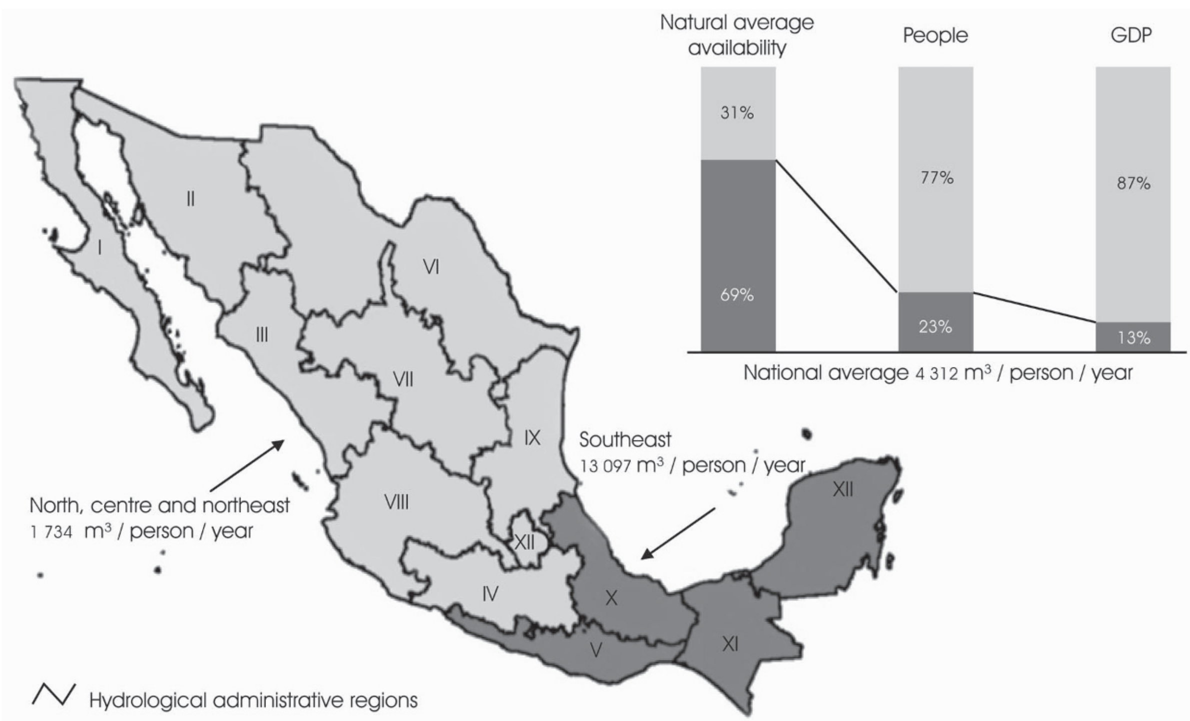


Figure 2.4: Regional contrast in terms of development and water availability. **Source:** CONAGUA (2008).



In Mexico, water availability in the 722 basins has been published in the Official Gazette of the Federation (Diario Oficial de la Federación, 2010) in the years 2003, 2005, 2007 and 2009. As can be seen in

Figure 2.5: Water availability in Mexico. **Source:** CONAGUA (2008b).

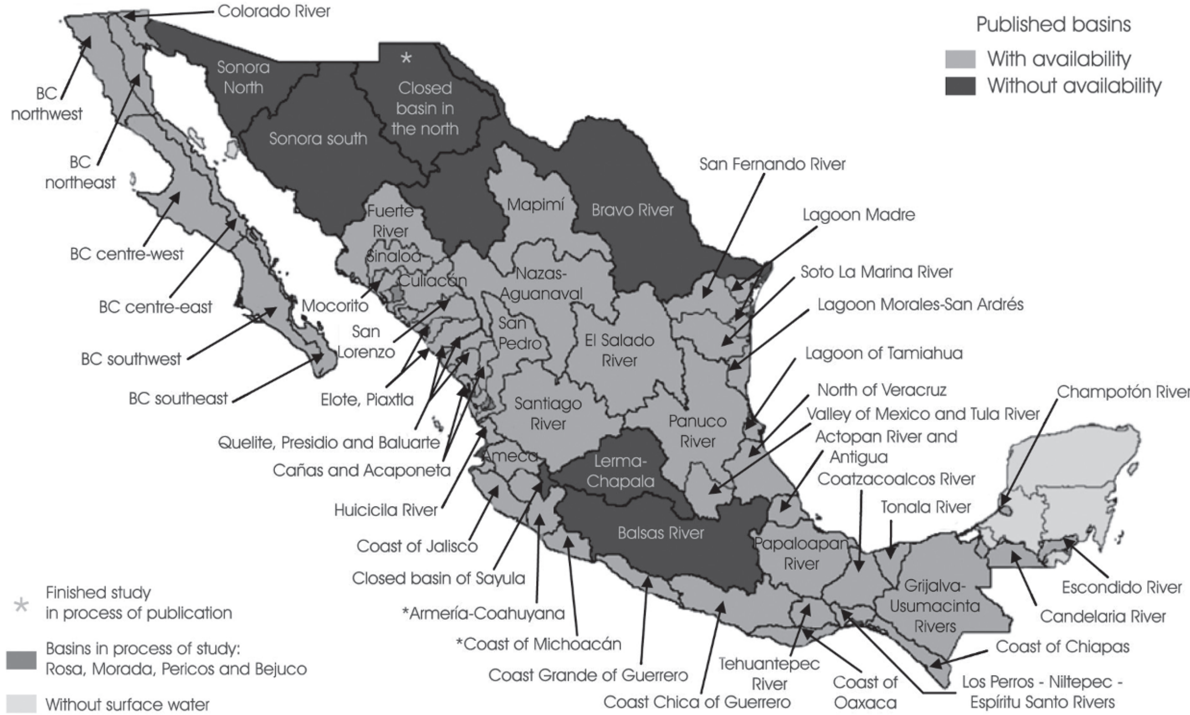


figure 2.5, some basins no longer have water availability because of over-exploitation. In this regard, the basins in the regions of the Bravo River, Lerma-Chapala, Balsas and the Peninsula of Baja California may be mentioned. Also, in almost all of the Yucatan Peninsula there are no surface currents.

Not only do the basins with greater socio-economic development have a deficit, but many other aquifers have also been over-exploited. In the Official Gazette of the Federation (Diario Oficial de la Federación, 2003, 2007a, 2007b and 2008) the average available water capacity of 282 aquifers out of the total of 653 (figure 2.6) was published, representing 93 per cent of total groundwater extraction. Again, aquifers in the centre and north of the country have a greater water extraction rate than the average rate of natural recharge.

2.2 Water Use

Out of the 78.9 km^3 of water used for different economic activities in the country, 77 per cent is destined for agricultural use, 14 per cent for urban use, 4 per cent for industrial use, and the remaining 5 per cent goes to cooling systems in thermoelectric plants (figure 2.7). Sixty three per cent out of all consumptive water is extracted from surface sources, whereas the remaining 37 per cent comes from underground sources. It is noteworthy that 122,800 million m^3 of water are used in hydroelectric stations in Mexico (non-consumptive water use).

2.3 Risks and Challenges

Mexico, like many other countries in the world, faces great water challenges. The most important are: the impact of climate change that will be addressed only in its relation to the water cycle, water pollution, water scarcity, poor water administration, lack of resources for research and technological development, and lack of environmental planning.

2.3.1 Climate Change

Perhaps the most important water challenge (and risk) that Mexico faces is the impact of climate change on water resources. These effects, as a consequence of global warming, refer to hydro-meteorological events in many regions of the planet: torrential rain, drought, changes in rainfall patterns, and more destructive tropical storms as well as hurricanes, among many others. Most scientists attribute global warming to the effects of greenhouse gases, especially

Figure 2.6: Availability of groundwater. **Source:** CONAGUA (2008b).

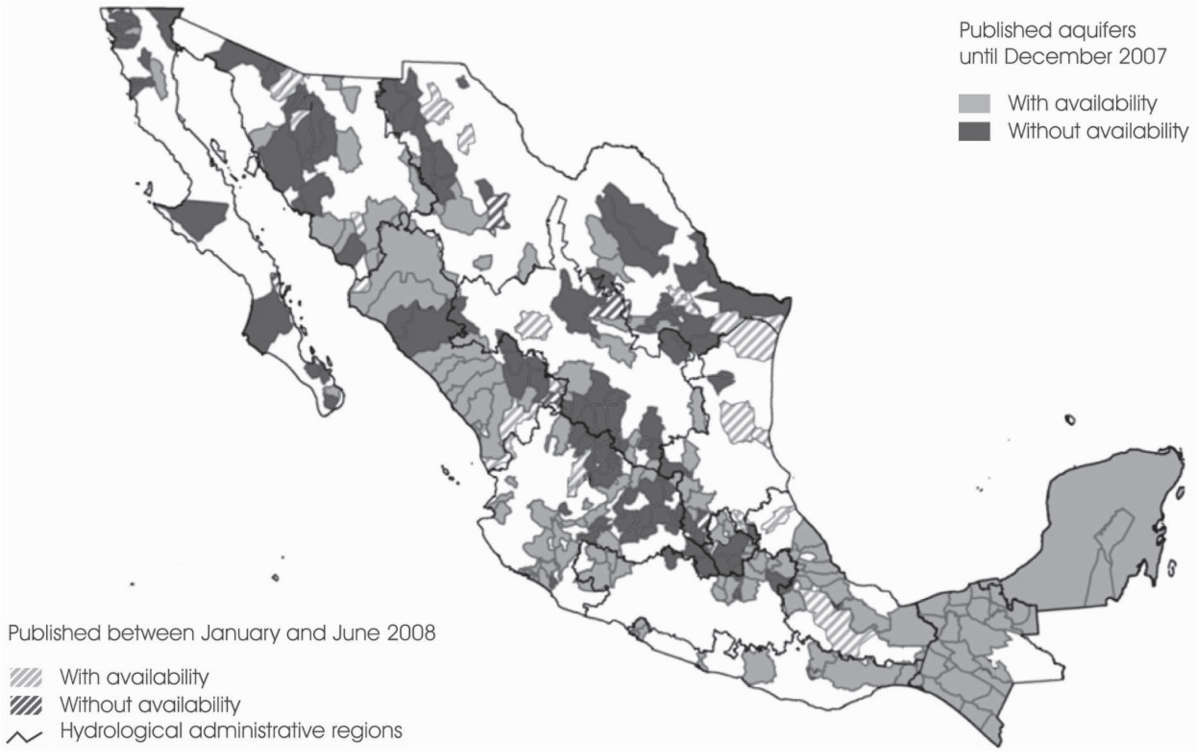
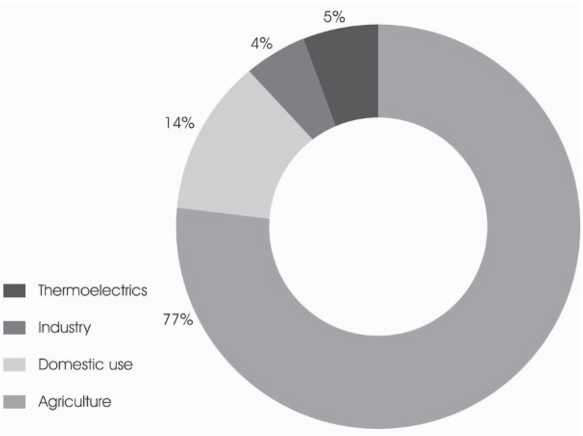


Figure 2.7: Water use in Mexico. **Source:** CONAGUA (2008b).



to carbon dioxide concentrations in the atmosphere (figure 2.8).

An indicator of global climate change is rising sea levels (figure 2.9) due to melting glaciers and polar ice that affect the temperature and mass of sea water. This implies grave risks to life in the North and South Poles, in the sea, and in coastal areas, which will be the first to seriously experience this effect.

Climate change affects the hydrological cycle in many ways, for example through

1. rising sea levels;
2. reduction and loss of perennial and seasonal ice;
3. more intense and frequent heat waves;
4. change in rainfall patterns;
5. more severe and frequent storms;
6. loss of adaptation of the groundcover given these new conditions;
7. more severe and lasting droughts;
8. increasing evapotranspiration and changing precipitation;
9. decreasing water discharge capacity of rivers into the sea;
10. increased rainfall in high latitudes, reduction of rainfall in low latitudes, with emphasis in the world's arid belts;
11. increasing destructiveness by tropical cyclones;
12. changes in areas prone to cyclones and tornados;
13. alteration of the global thermohaline circulation as excess fresh water is being discharged into the sea;
14. more water vapour in the atmosphere causing low or high clouds; and
15. irreversible changes (in the short term) in re-emission of energy to space by areas that have lost their ice cover.

Figure 2.8: Increase of carbon dioxide concentration in the atmosphere and global rise of temperature in the past thousand years. **Source:** Oak Ridge National Laboratory, at: <http://cdiac.esd.ornl.gov/trends/temp/jonescru/jones.html> (based on Johnes/Mann, 2004 for the years 1000-1880, and for the years 1820 to 2005 on Johns/Parker/Osborn/Briffa, 2005).

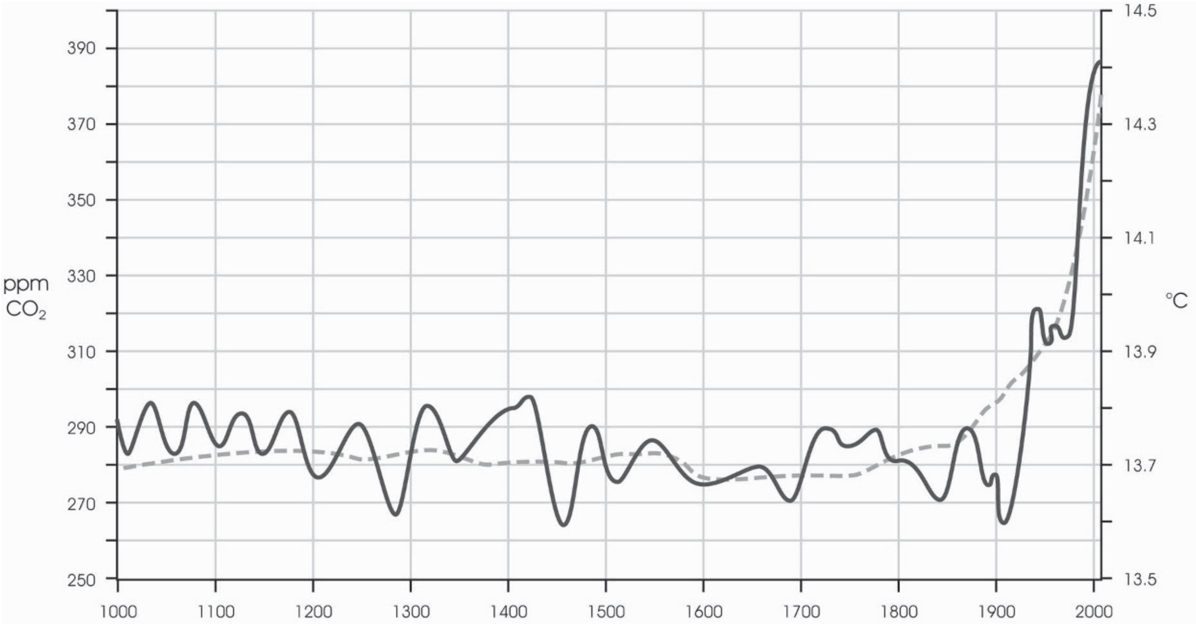
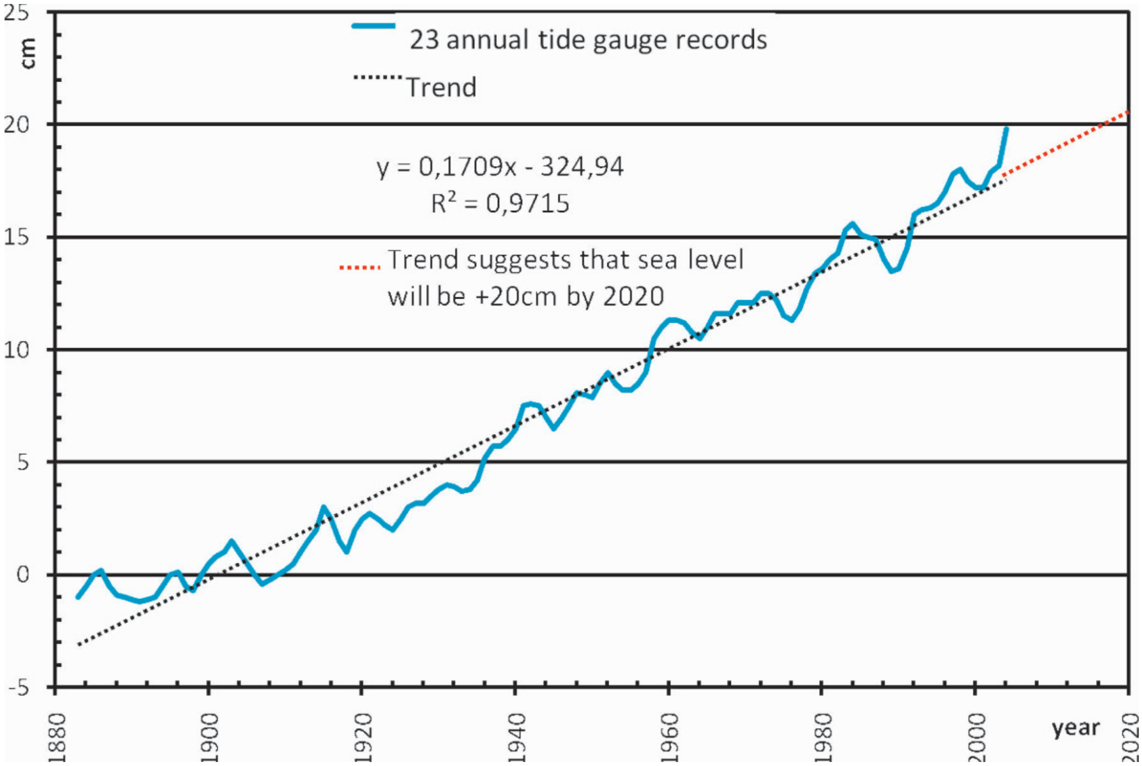


Figure 2.9: Sealevel variation (period 1883-2004). **Source**: Modified and extended by the authors based on Douglas (1997).



Some changes in meteorological events have already been registered in Mexico; for example, the occurrence of severe storms has significantly increased. In the year 2008 there were 632 heavy storms (with more

Figure 2.10: Behaviour of maximum temperature in Mexico, 1961-2040. **Source:** Arreguín, Chávez and Rosengaus (2008).

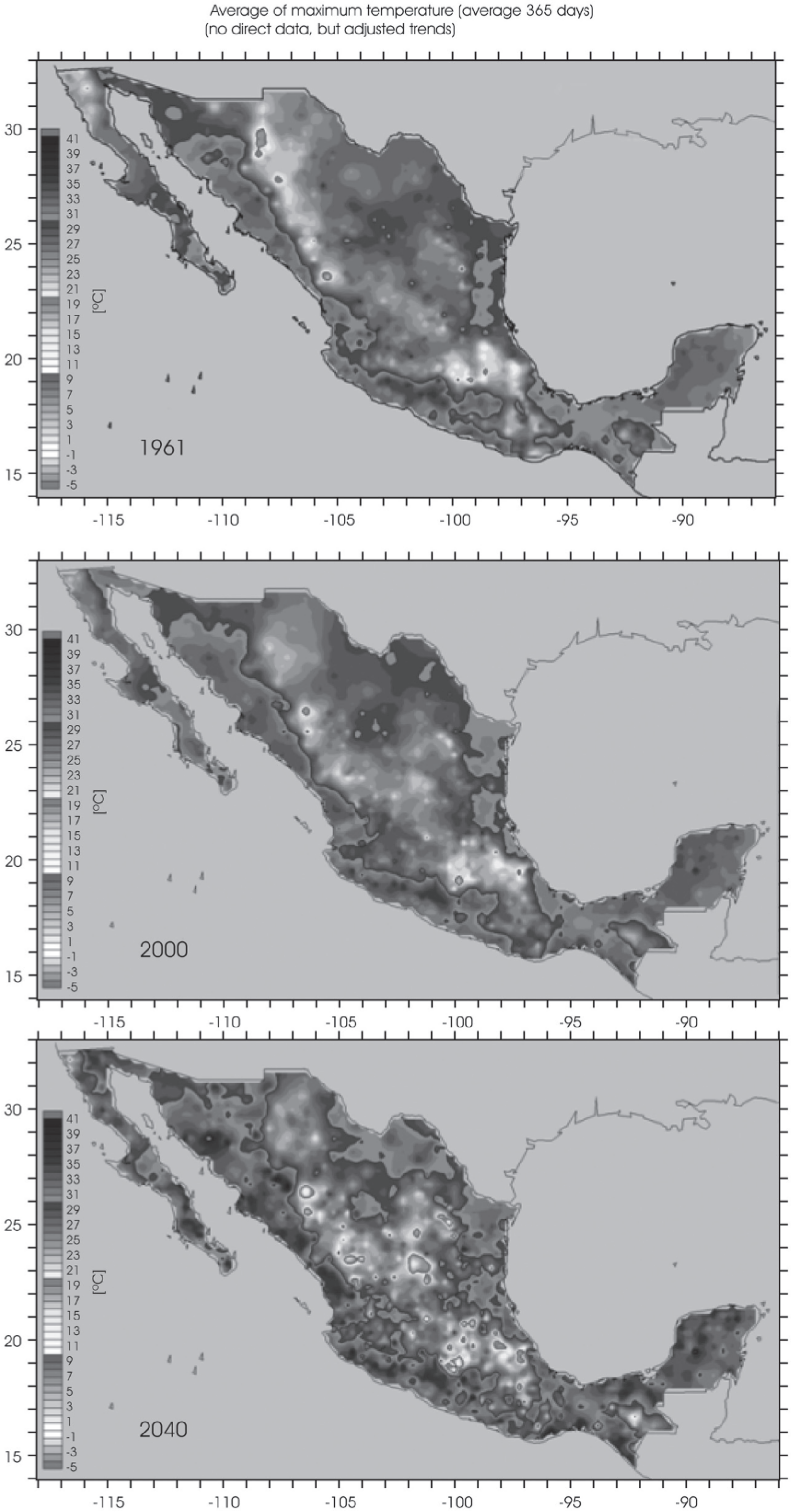


Figure 2.11: Minimal temperature behaviour, 1961-2040. **Source:** Arreguín, Chávez and Rosengaus (2008).

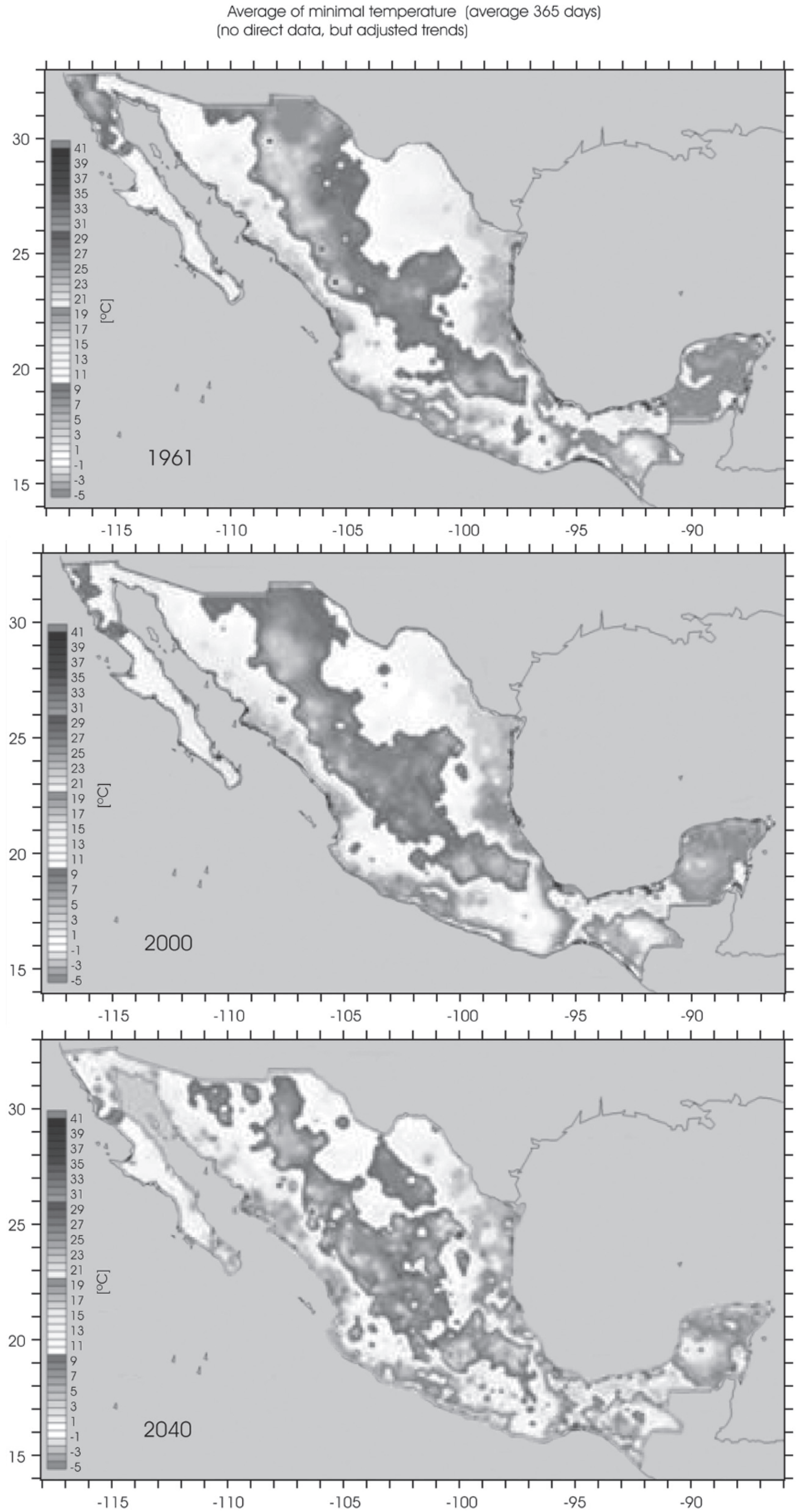
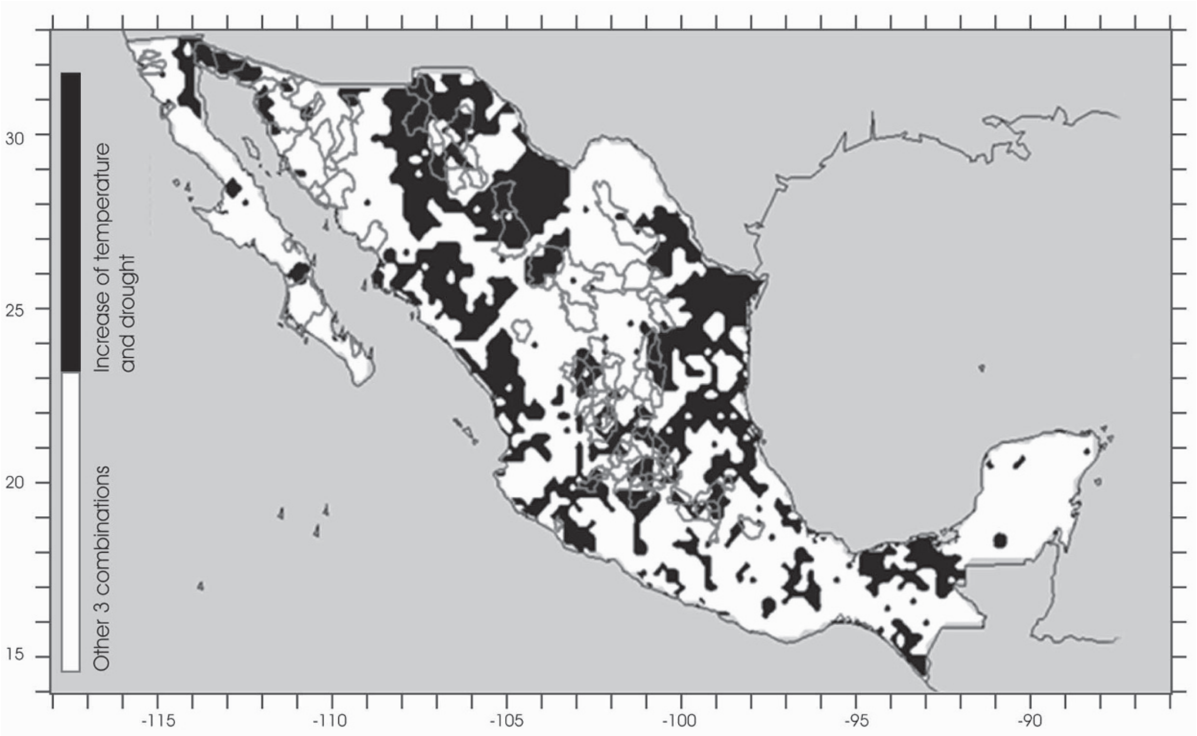


Figure 2.12: Currently over-exploited aquifers where an increase of temperature and a decrease of rainfall is expected in the year 2040. **Source:** Arreguín, Chávez and Rosengaus (2008).



than 70 mm of rainfall within 24 hours), compared to an average of 469 registered storms between the years 1996 and 2007; that is, an increase of 34.75 per cent. The year 2008 surpassed the year 2003 that held the historical record with 544 severe storms.[2]

Taking measures obtained from the meteorological web of the National Water Commission for the period 1961–2000, a database called *Maya v1.0* was constructed. This is a structured and ordered database for the purposes of conceptual analysis with useful data, such as "4,542 weather series, each of 14,600 days" or "14,600 maps". Graphically, it is a regular web with a resolution of 20 km between each node (Rosengaus, 2007). The values between the nodes were mathematically calculated with the data measured by the web, using sound statistical techniques.

This database allows us to graphically portray the patterns of rainfall and temperature in the national territory and to make projections for the following forty years (figures 2.10 and 2.11). However, caution must be exercised as these calculations have not included the chemistry and physics of the atmosphere.

Based on this information, predictions can be made by combining the maps of temperature and rainfall with those of over-exploited aquifers to identify the areas where temperature will increase and rainfall decrease, thus impacting on water availability. In this case, the areas of the north-west, central north, north-east and south-east of Mexico will be the most affected, as water availability will decline (Arreguín/Chávez/Rosengaus, 2008; figure 2.12).

Aquifers will also be affected by rising sea levels as this will increase the risk of saline intrusion into coastal aquifers. The situation is particularly grave in the aquifers that are already threatened by this phenomenon (figure 2.13).

Given its geological and hydrological characteristics, the Yucatan Peninsula is especially vulnerable to saline intrusion. It is made of karstic material, has no surface currents, and all rain water that is not evaporated infiltrates the ground. Groundwater is abundant but the aquifer is shallow; the salt wedge penetrates widely. Given these characteristics, water moves through fissures or fractures that make formations such as cenotes and underground rivers. Thus, any increase in the average sea level will easily infiltrate inside the territory and significantly reduce fresh water.

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2 National Meteorological Service (2009); at: <http://smn2.cna.gob.mx/SMN2/Default.aspx>.

Figure 2.13: Aquifers currently affected by sea water intrusion. **Source:** CONAGUA (2008b).

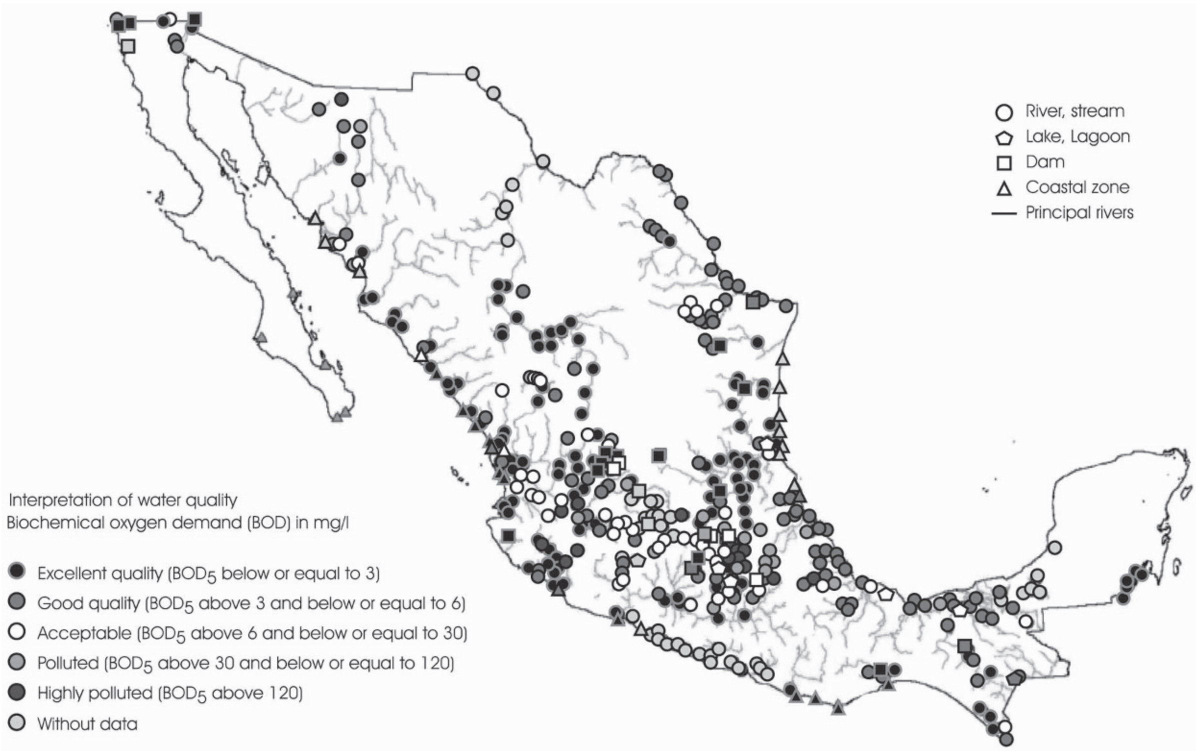
In addition, an increase in the average sea level will reduce the natural discharge of rivers, causing floods in lowlands. As a consequence, the coast will move inwards into what today is considered as terra firma. Given their devastating impact, tropical cyclones are among the most important hydro-meteorological phenomena affecting Mexico. Most scientists foresee an increase in their frequency, as well as in their level of destructiveness. Growing populations settled in high risk areas will be especially vulnerable due to the lack of environmental planning.

One of the greatest preoccupations of Mexico related to climate change is the ability of the country to comply with international commitments relating to water, for example the 1944 Water Treaty between Mexico and the United States of America. In general terms, Mexico obtains a higher portion of this water compared with the USA, although it is still difficult to comply with this international commitment because of the poor administration of water resources in the north of Mexico and to the extraordinary droughts in the region. Recently, the basin of the Colorado River has experienced such severe drought that the levels in the dams have reached historically low levels, and both countries are examining the possibility of implementing extraordinary measures such as making use of additional water sources and heavy investment in action to safeguard water resources.

For this reason, several techniques for water conservation are being considered: the recovery of water linked to the exploitation of methane; the control of evaporation in water storage through chemical covers and the operation of dams; water imports through oceanic routes, through water pipelines below sea level from the rivers of northern California and from other basins; with ships from Alaska; with water bags and by towing icebergs; desalinizing brackish waters from aquifers in Yuma, Arizona and Riverside, California, as well as sea water from the Pacific Ocean; the integrated management of surface and groundwater; collecting and storing rain and storm water; removal of vegetation along the river to reduce evapotranspiration; reducing consumptive use by thermoelectric plants; water reuse and recycling; and weather modification by cloud seeding in the basins of the upper Colorado River. These examples indicate both the urgent need to find alternative water sources on the one hand and to extend the possibilities to deal with problems in each basin on the other hand (Colorado River Water Consultants, 2008).

Only a few examples were cited of the impact that climate change may have on the hydrological cycle in some regions of the national territory, although most of them will indeed affect Mexico.

Figure 2.14: Biochemical oxygen demand in Mexico, 2007. **Source:** CONAGUA (2008b).



2.3.2 Water Pollution

Biochemical oxygen demand (BOD) is a domestic and municipal indicator of pollution. The hydrological and administrative regions of the Valley of Mexico, Northern Gulf, Lerma Santiago Pacific and some areas in the Central Gulf show higher pollution (figure 2.14).

The other parameter frequently used to measure water quality is *totally suspended solids* (TSS). The occurrence of TSS in water bodies in Mexico indicates problems especially in the coastal zones from Colima to Guerrero, in the south of Veracruz and Tabasco, as well as important pollution areas in the rivers Santiago, Lerma, Bravo and Soto La Marina. Generally, the core challenges for water quality are that wastewater treatment plants should comply with quality norms, and that standards are established for flows and receiving bodies. Also, studies in the Lerma River sub-basin have reported data suggesting an important impact by diffuse pollution. This constitutes an aspect that has hardly been investigated in Mexico, research that is most pressing in order to adopt the necessary control measures. Beyond the necessary investments, the most important issues at stake are the values and conscience linked to living together in a clean environment.

2.3.3 Water Scarcity

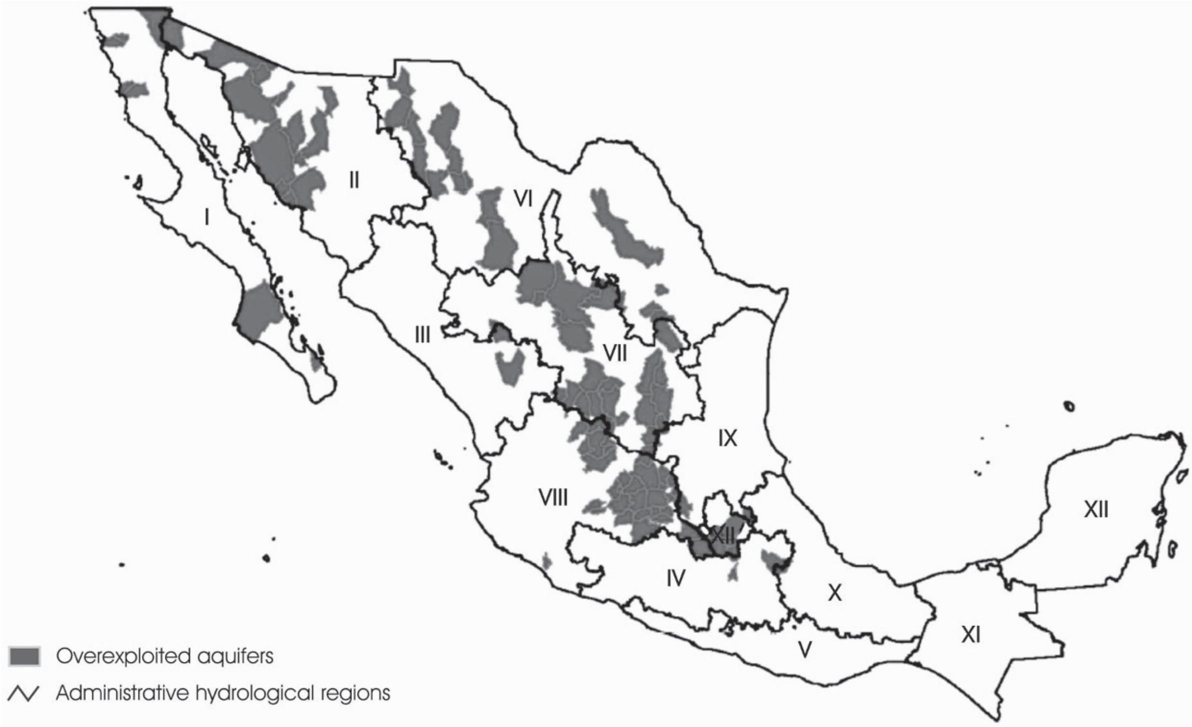
As was mentioned in the first section of this chapter, water scarcity in a country where two-thirds of the national territory is arid or semi-arid implies important problems in terms of water availability, which in turn hinders development. Over-exploitation of aquifers is particularly worrying; current estimates are that there are 102 over-exploited aquifers out of a total of 653. This situation is most notable in the hydrological and administrative regions of the Valley of Mexico, Lerma, Chapala, Central Basins, Bravo and the Northwest (see figure 2.15).

The challenge is to reduce the over-exploitation of groundwater without affecting social and economic activities, allowing a sustainable exploitation of aquifers so that the processes of water extraction and recharge of aquifers fall into equilibrium.

2.3.4 Improving Water Management

Lack of water is not only due to water scarcity and pollution. The cornerstone of water management in

Figure 2.15: Over-exploited aquifers by hydrological and administrative region. **Source:** CONAGUA (2008c).



Mexico is the National Water Law. This law, amended in the year 2004, still requires a profound reform to revert amendments, and perhaps even its derogation and the creation of a new law altogether. This is because when the National Water Law was published in the year 1992, many innovative concepts were included, such as sustainable management and integral planning; social participation in hydraulic planning, in the water market and in concessions; public information in terms of water quality, availability and use; and the Basin Councils. However, using the argument that limited advances had been made in terms of water management, amended concepts and time limits were promoted in order to put pressure on and oblige the water authorities to correct the problems of over-exploitation, pollution and sanitation. The truth was that many concepts of the 1992 Law were never applied, or their implementation was rudimentary, and thus it was impossible to evaluate their usefulness or efficacy. The clearest examples are: the environmental variable, the publication of water availability, the actualization of regulatory instruments (closed seasons, environmental reserves and regulations), the classification of water bodies, the water market, and the Basin Councils and their auxiliary groups. Analyzing what has occurred within the legal framework during the past twenty years, it is evident that efforts were geared towards amending the National Water Law and its regulations in the hopes that those changes by themselves would suffice to transform the water situation in Mexico. The recurrent failure has been to overlook that no law or amendment can be applicable if institutional capacities and the resources of water authorities, state governments, Basin Councils and other agents surrounding water have not been considered.

It is also clear that water administration is not only in the hands of water authorities; looking after water is a task that involves society as a whole. In this regard it is pertinent to mention the observation stated in the UNESCO's 2nd World Water Development Report:

> A basin insight – which has not yet garnered enough attention – is that the insufficiency of water (particularly for drinking water supply and sanitation), is primarily driven by an inefficient supply of services rather than by water shortages. Lack of basic services is often due to mismanagement, corruption, lack of appropriate institutions, bureaucratic inertia and a shortage of new investments in building human capacity, as well as physical infrastructure. Water supply and sanitation have recently received more international attention than water for food production, despite the fact that in most developing countries agriculture accounts for 80 percent of total water use. It is increasingly agreed in development circles that water shortages and increasing pollution are to a large extent socially and politically induced challenges, which means that there are issues that can be

addressed by changes in water demand and use and through increased awareness, education and water policy reforms. The water crisis is thus increasingly about how we, as individuals, and as part of a collective society, govern the access to and control over water resources and their benefits (UNESCO, 2006).

A new National Water Law, with an adequate balance between state and municipal laws, is without doubt the necessary basis for efficient water management in Mexico.

2.3.5 Investment in Research and Technological Development

Over the past years there have been advances in terms of research, technological development and human resource building in the hydraulic sector. However, it is necessary to organize and take advantage of the institutional capacity of technological development and research centres, universities, and businesses, through a wider structure that coordinates all the efforts surrounding a common objective. In Mexico, the total budget allocated to science and technology in relation to the *gross domestic product* (GDP) is 0.37 per cent. This reality reflects an investment that is six times lower than the 2.26 per cent average in OECD member countries. Thus, it is necessary to increase investment in science and technology to at least one per cent of GDP (Ruiz, 2009).

One area of opportunity is the development of synergies between governments, universities and businesses, so as to build the human capital of students, public servants and researchers that the country needs. These types of strategic alliances would facilitate goals such as:

1. preparing the new generation of engineers in order to develop the infrastructure Mexico needs;
2. fortifying schools of engineering in the country;
3. strengthening businesses that deal with project engineering and construction;
4. developing cutting-edge research for both the public and private sector;
5. boosting and updating research capacity;
6. transferring knowledge and technologies to the public and private sectors; and
7. promoting a culture of entrepreneurship and the creation of businesses with a sound technological base.

2.3.6 Environmental Planning

Recent floods in many regions of the country, the impossibility of offering drinking water and sewage due to the dispersion of the population, environmental law violations such as invading river beds and flood-prone areas, excessive deforestation throughout the national territory, and other similar actions are the main obstacle to a sound water management. Urban growth and competition for land use have led to the occupation of flood-prone areas (and also to those that were originally not flood-prone), river beds, and to the invasion of areas within natural and artificial water bodies.

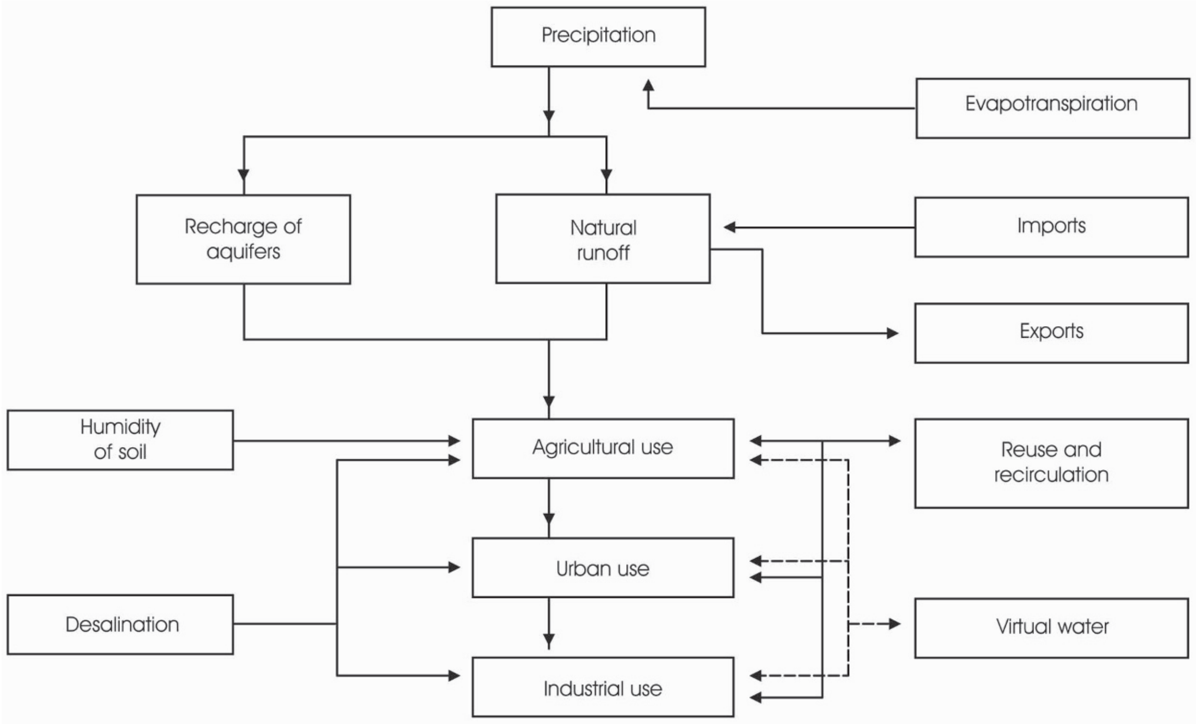
2.4 The National Water Programme (2007-2012)

To solve these problems, the National Water Commission developed the National Water Programme 2007–2010 (PNH, 2008) under the present federal public administration following the Planning Act (LP, 83), in accordance with the National Development Plan 2007–2012 (PND, 2007), in order to face present and future water challenges. The objectives of the National Water Programme are:

1. improving water productivity in the agricultural sector;
2. increasing access and quality of potable water services, sewage and sanitation;
3. promoting an integral and sustainable water management in basins and aquifers;
4. improving the technical, administrative and financial development of the hydraulic sector;
5. consolidating the participation of water users and organized society in general in water management, and promoting a culture of efficient water use;
6. preventing risks posed by hydro-meteorological events and overcoming their effects;
7. evaluating the effects of climate change in the hydrological cycle; and
8. forging a participatory culture and fostering compliance with the National Water Law in administrative terms.

Each of these objectives is further split into different strategies and programmes with clearly outlined goals. To date (2009), developments have come very close to meeting targets.

Figure 2.16: Proposal for a national water balance. **Source**: Arreguín et al. (2007).



2.5 Proposal for a New Water Balance

The national water balance should be re-evaluated in order to make better use of water where it is available, and to take it to regions where it is scarce. The proposal is to amend the traditional water balance scheme of the country (figure 2.16). The four elements added to the conventional scheme are outlined below.

2.5.1 Water Reuse and Recirculation

According to estimates annually 431.7 m^3/s of wastewater are produced. Of these 243 m^3/s come from municipal sources and 188.7 m^3/s from non-municipal sources. From the municipal wastewater sources, 207 m^3/s are collected, namely 85 per cent, of which 83.8 m^3/s are treated. In the case of non-municipal wastewater discharges, 29.9 m^3/s are treated, representing 15.8 per cent of the total. It is also noteworthy that 63.52 m^3/s of non-municipal wastewater discharges come from sugar refineries and that they are used for the irrigation of fields with sugar cane.

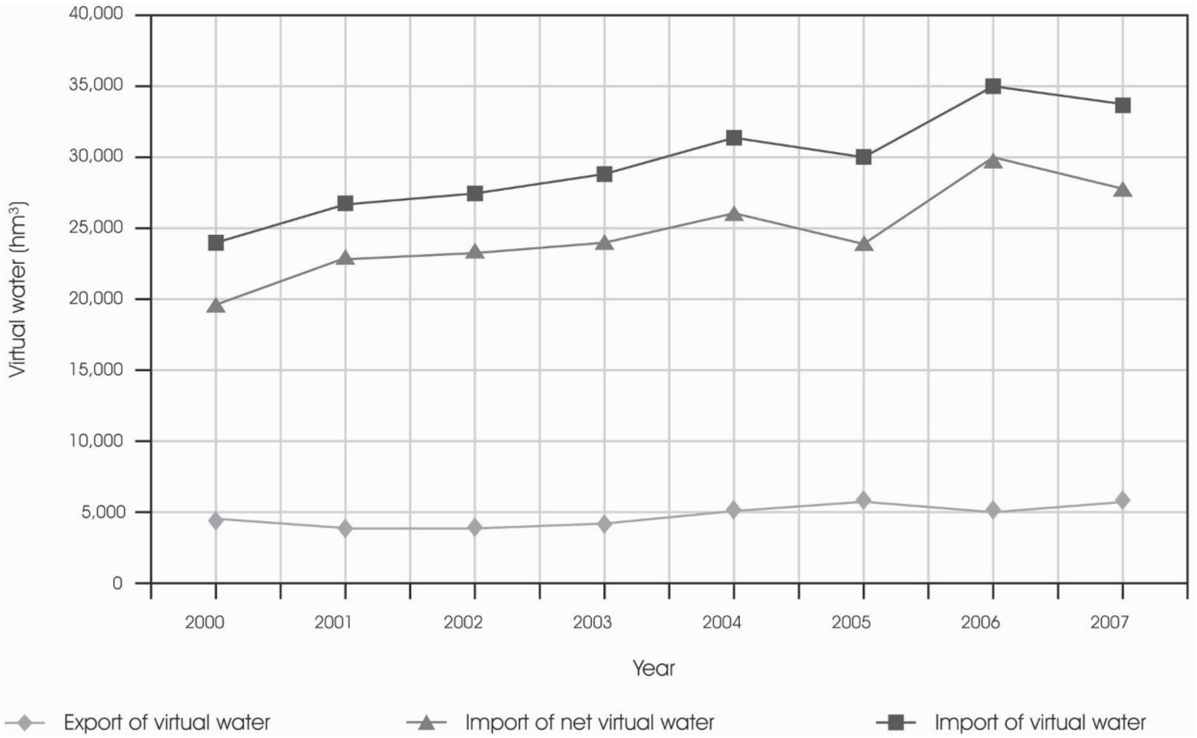
So, even though we are dealing with the reuse of 60 per cent of municipal water, at a later stage the plan is to reuse non-municipal wastewaters also. If the amount of the collected wastewater discharges should increase, this water could be reused in industry or for irrigation. Although in absolute terms the overall amount of reused water would seem minor, it is important to note that wastewater discharges are near human settlements or irrigation areas, making them easily suitable for that purpose. Besides this, water recirculation could add new water sources to industries instead of their depending on the habitually overexploited freshwater sources.

2.5.2 Virtual Water

There is a way of transporting water without using aqueducts, ships or tankers, and of storing it without needing dams, cisterns or tanks - what is called *virtual water*. Virtual water is the amount of water used in the production of a product, good or service. For example, in order to produce a ton of wheat it is necessary to use 1,000 m^3 of water on average.

Thus, countries with important industrial or oil developments but with scarce water resources for producing food, goods and services may use their financial resources to purchase them from other countries that have enough water to produce and export them. Thus, instead of using their scarce water resources to

Figure 2.17: Amount of net virtual water imported into Mexico (2000-2007). **Source:** Arreguín et al. (2009).



produce agricultural or industrial goods, by importing them, these countries reduce the pressure on their water resources.

The concept of virtual water has strengthened with the increasing importance of the environmental, economic, social and political value of water. In the period between 1995 and 1999, 1,031 km^3 of virtual water were negotiated annually in the international market (Hoekstra/Chapagain, 2006).

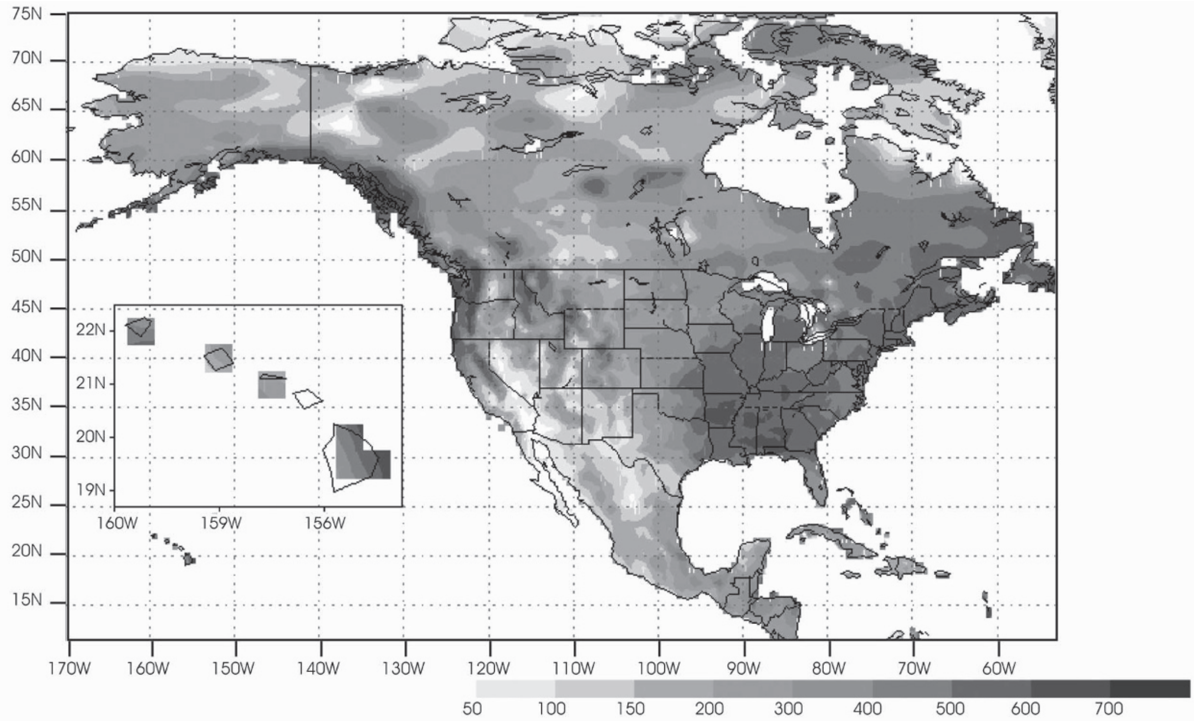
Thus, virtual water has been very important in countries that lack water resources for producing food, goods and services on a permanent basis. However, it has also played a decisive role in countries that have faced extreme weather events such as droughts and hurricanes. In several other countries virtual water has been useful in reducing the pressures on the environment. But virtual water also depends on other factors such as international trade agreements and treaties, on the population and economic growth, on technological advances, agricultural subsidies, international prices of agricultural products and inputs, on the countries' macroeconomic policies relating to imports and exports, on microeconomic policies, on the culture and religion of the producers, and on efficiency in agricultural and industrial production.

Figure 2.17 documents the evolution of imports and exports of virtual water in Mexico. In 2007 Mexico exported 5,884 hm^3 of virtual water but it imported 30,097 hm^3, which amounts to a net virtual water import of 24,213 hm^3 (Arreguín et al., 2007, 2008a, 2009).

2.5.3 Desalination of Water

Water desalination is a technology that has been used in Mexico for a long time, especially in tourist areas where water is scarce, such as Cancun in Quintana Roo, Acapulco in Guerrero, and Los Cabos in Baja California Sur. However, it has only been since the construction of a desalination plant for municipal use in Los Cabos that consideration of the use of this technology has become widespread throughout the country. Currently, desalination has been considered for agricultural use in cases where crop economics make it feasible (for example, to grow flowers and vines). Furthermore, desalination is at present being contemplated for big development projects in Rosarito and Ensenada in Baja California, in Puerto Peñasco in Sonora, and even in the Colorado River Basin to enable Mexico to comply with the requirements of its international water treaty with the USA. The progressive decrease in the cost of a cubic metre (m^3) of desalinized water and the increase in water demand position this technology as one of the main

Figure 2.18: Soil moisture for May 2009 (in mm). **Source:** CPC and NOAA (2009); at: <http://www.cpc.ncep.noaa.gov/soilmst/leaky glb.htm>.



sources of water supply in places where it is economically, environmentally and socially sound to implement it. In Baja California, there are cases where a cubic metre of desalinated water costs 9 or 10 pesos on average.

However, it is important to bear in mind that, out of the 435 desalination plants in Mexico, 137 are inactive due to a lack of adequate training and on-going training, long lead times, shortage of stock of specialized tools and reserve pumps and their being close to enterprises with high levels of oil, grease and organic waste discharges. These elements should be considered in order to prevent the abandonment of those desalination plants that are effective in areas of water scarcity such as the Yucatan Peninsula, Baja California and Sonora (ITSON, 2008/2009).

Environmental impact: Installing and operating a desalination plant has the potential of negatively impacting on air quality, aquifers, marine and aquatic environments, and possibly also on other aspects of mitigation. All these factors should be considered when assessing desalination plants in local and national regulation policies. Also, studies to evaluate potential construction sites should be undertaken and complemented by monitoring programmes after installation.

Among the relevant aspects to be considered are:

- *Construction:* the ecology of coastal zones and sea bottoms, habitat of mammals and birds; erosion and pollution effects far away from the point of discharge;
- *Energy:* fuel sources and transportation, discharge of cooling waters, air emissions as a consequence of fuel burning, and electric energy production;
- *Air quality:* links to energy production;
- *Marine environment:* components of discharges into the ocean, thermal effects, sea water extraction processes, effects of biocide compounds and toxic metals in discharged waters, oxygen levels, cloudiness, salinity, water mixing zones, impact on commercial fishing, recreation and tourism, amongst others;
- *Aquifers:* increase in soil salinity and possible toxic metal deposits in unconfined deposits.

2.5.4 Soil Moisture

Soil moisture is frequently based on peasants' knowledge, although it is rarely derived from a sound scientific base. In hydrology, soil moisture is defined as the liquid water content in a given earth surface. The *Climate Prediction Center* (CPC) of the *National Oceanic and Atmospheric Administration* (NOAA) of the

US publishes official maps on a monthly basis such as the one displayed below (figure 2.18).

2.6 Conclusions

Mexico faces considerable water challenges such as pollution, the impact of climate change on the hydrological cycle, water scarcity, the strengthening of water management to involve all users, and the need to revise and fortify science and technology in the country, as well as to promote sound environmental planning. However, Mexicans have the means to meet these challenges such as the National Water Programme, which governs all matters relating to water. It is essential to face these challenges as soon as possible and policies should be based on scientific grounds, always taking the environmental, social, economic and political aspects of water governance into account.

The current problems in Mexico have old historical roots, deriving from the country's socio-economic evolution and from water abuses, over-exploitation of aquifers, scarcity of surficial waters, pollution, and especially the low value that society confers on this most precious resource. Nevertheless, these are also the existing areas of opportunity, the challenges and menaces the country faces, which must be overcome if the country is to guarantee water for its future generations.

Technologies are constantly improving; this also applies to new forms of organization and articulation that include all actors related to water. It is imperative to strengthen the number of students, public servants, entrepreneurs and researchers working on issues that relate to Mexico's water challenges. This is the way forward and Mexico cannot afford to miss this opportunity.

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3 Integrated Water Management in Hydrological Basins: Multidisciplinary and Multi-Institutionality as an Action Paradigm

Ignacio Sánchez Cohen, Úrsula Oswald Spring, Gabriel Díaz Padilla and José Luís González Barrios

3.1 Introduction

The variability in space and time of natural processes – especially the weather – together with market uncertainties and the globalization of the economy are factors that have led decision-makers to seek an integrated approach to facing the problems of water management and to integrating divergent interests. Such an approach offers the potential for balancing competing interests over water in hydrological basins (Sánchez et al., 2009). The wider definition of a basin includes policies, plans and activities used to control water and resources, as well as the human-induced processes that are associated with the basin. An integrated management approach has distinctive features as it seeks to balance institutional interests with those of the region and its stakeholders. It is a representative process that includes the research area and accounts for the opinions of all participants, in order to achieve an action plan that is accepted by the majority, thus reflecting a negotiated balance of interests. It also incorporates available scientific information in order to adequately understand hydrological as well as environmental factors that influence the condition of the basin. It also designs effective and participatory methods that involve all stakeholders in such a way as to distribute costs and benefits proportionally. As well as this, it constitutes a framework of agreements between different government offices, and within each office it guarantees the execution of the plans that were developed throughout the decision-making process, based on collective compromises, and conforming to the law. Finally, it also includes an ongoing basin management monitoring scheme with steps that can be easily measured.

According to Heilman et al. (2006), the core philosophical characteristic of all conservation plans for natural resources recognizes that the plan is developed by and for the producers, and its application includes conservation benefits for all. From this basis we derive (or we should be able to derive) an integrated water management, taking the basin as the basic planning unit for developing all natural and productive chains associated with it. Research undertaken to sustain these decisions should be geared to hydrological processes that intervene in water availability at three areas of the basin: the high region where precipitation is higher and run-off originates, the middle part of the watershed that is usually an agricultural zone with limited human settlements, and the lower part of the basin, where irrigation districts are usually located (Sánchez, 2002) as well as urbanization and aquaculture.

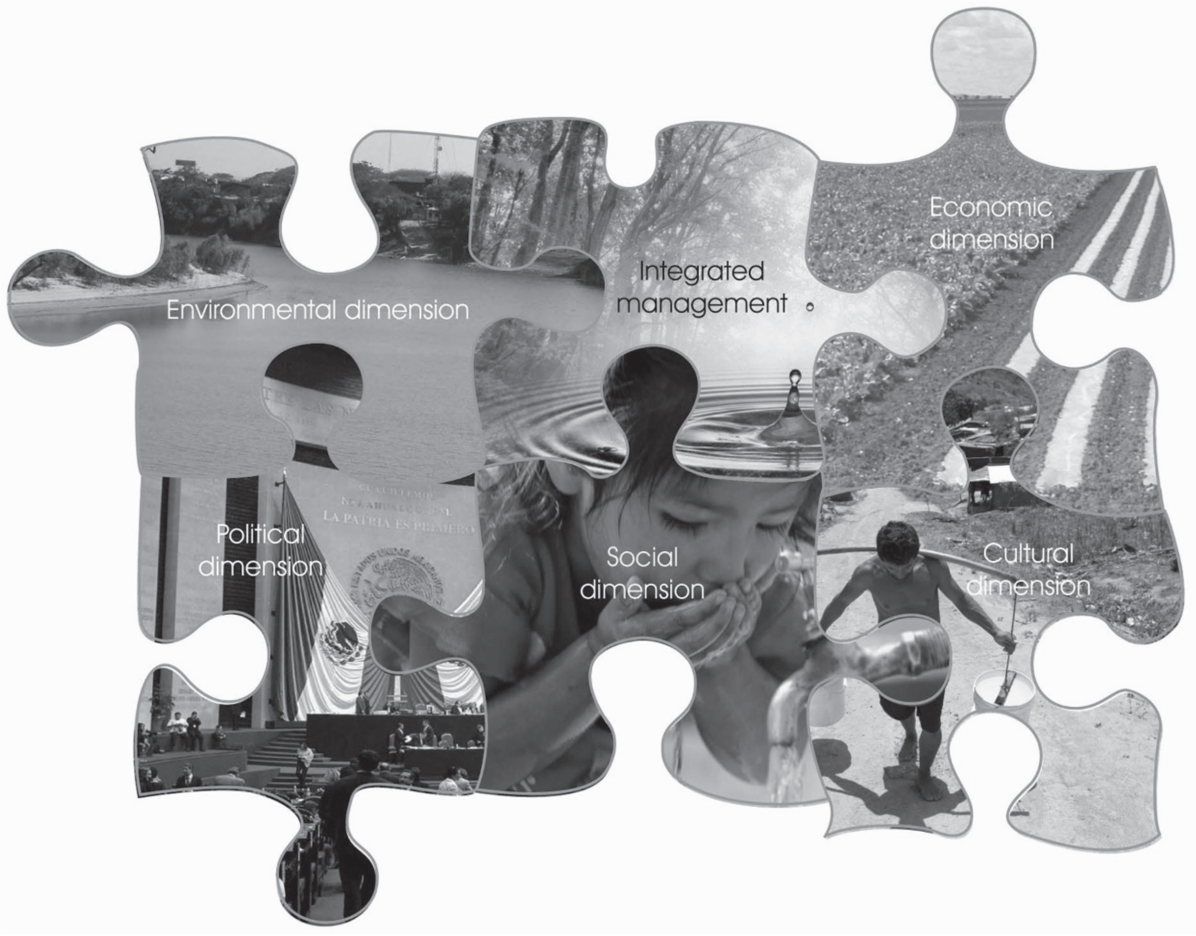
3.2 Approximation to an Integrated Water Management

Seeking a definition of the concept of 'integrated water management' requires a synthesis of numerous fields. It refers to the practice of making decisions and actions while taking into account a number of different viewpoints on how water ought to be managed. These actions and decisions are linked to situations such as planning the use of river waters, organizing available resources and efforts, designing new infrastructure, controlling water allocation, and developing new laws and regulations that consolidate water-related processes at the same time as making them more transparent.

The need to consider a variety of viewpoints leads to complexity. It emerges from numerous objectives and expectations in a region and links with competition over water resources, given different economic activities and interests as well as institutional restrictions. Thus, integrated water management will gradually approximate to solving problems and making structural changes in a way that is economically effi-

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*, Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_3,

Figure 3.1: Environmental dimension of an integrated water management with climatic and hydrological aspects. **Source:** Developed by the authors.



cient, socially equitable, environmentally sustainable, politically viable, and acceptable for all citizens (NRC, 1999). Conceptually, the integrated water management approach promotes the coordinated management and development of water, soil, and related resources, maximizing economic benefits at the same time as producing an equitable well-being, without compromising the sustainability of ecosystems.

Operationally, this approach involves knowledge drawn from various disciplines to integrate the interests of different stakeholders and groups that can be used to design and implement their own solutions, including considerations of efficiency, sustainability and equity. Thus, the essential objectives of integrated water management reflect the most important societal dimensions such as political, economic, cultural, social and environmental aspects (figure 3.1; Sánchez/González/Díaz/Velásquez, 2009).

3.2.1 Administrative Aspects

Administratively, the concept of integrated water management is that part of environmental management that involves the management of natural resources in a framework that is both multi-sectorial and domain-specific. In this context, the hydrological basin appears as the basic unit of planning and of the development of productive chains (figure 3.2).

Multidisciplinarity is the ideal context for the development of research and productive processes for integrated water management, and it is linked to complex interactions between water, climate, soil, plants, animals, human beings and productive activities (Sánchez, 2009). This makes it ineffective to consider mono- objective actions and isolated single-disciplinary studies. The arguments that support the hydrological basin as the basic unit of multidisciplinary planning are:

Figure 3.2: Administrative mapping of the concept of Integrated Water Management. **Source**: Developed by the authors.

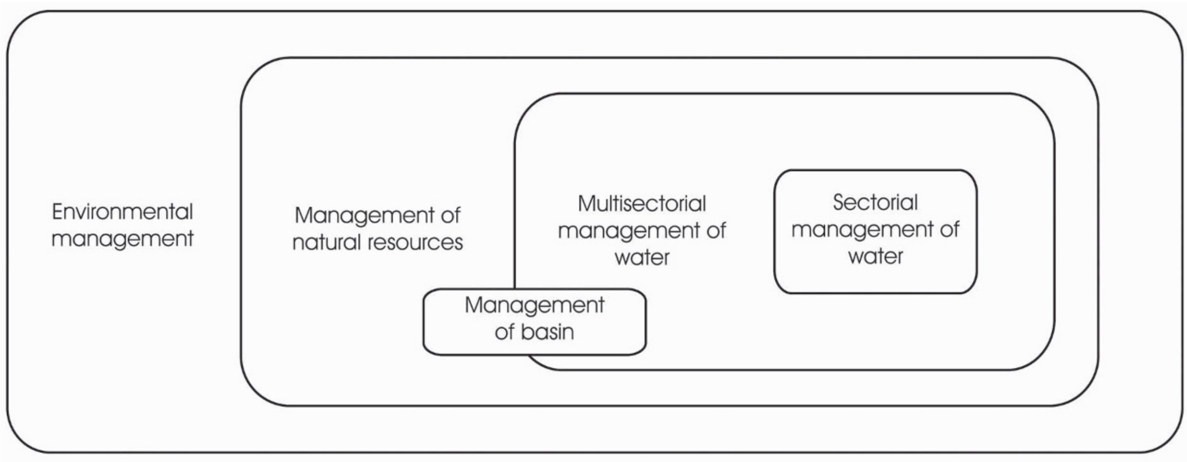
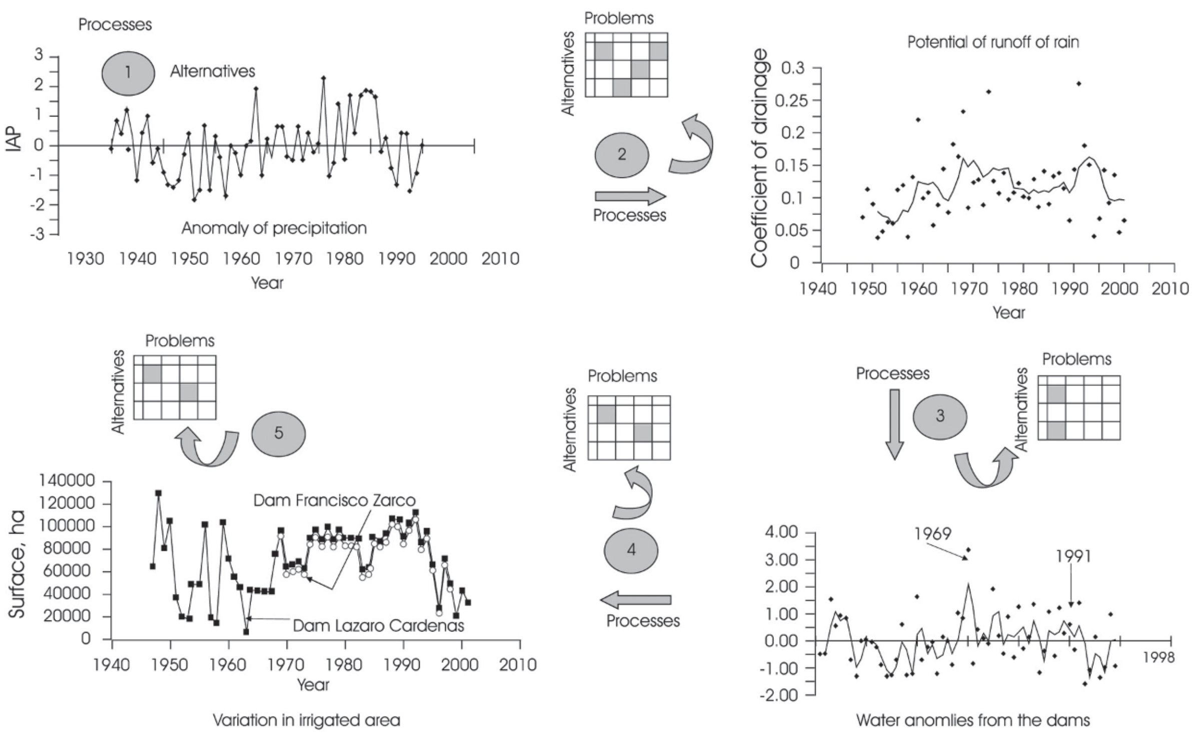
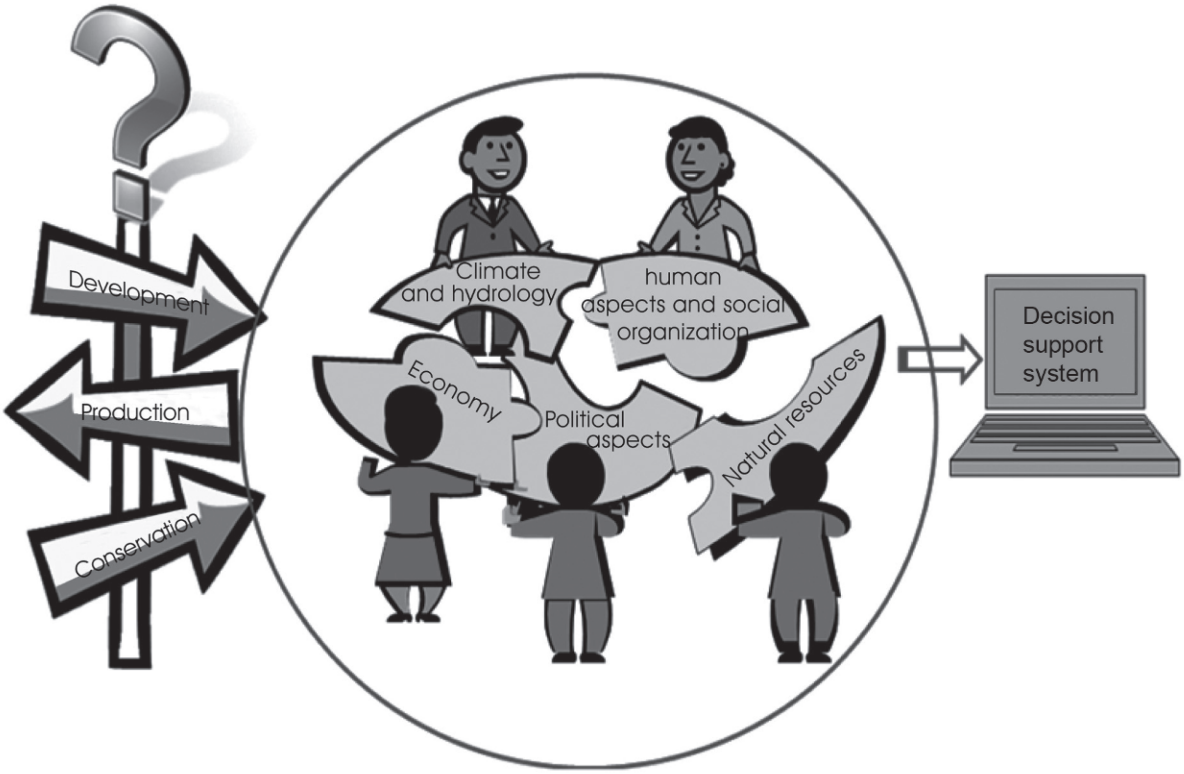


Figure 3.3: Conceptual model of the cascade effect stemming from precipitation problems in basin RH36. The grids portray gaps in knowledge. **Sources:** Sánchez (2005: 44); Sánchez et al. (2006: 2, 2007: 13).



- Complex interactions require a balance between institutional and productive processes, with the negotiation of integrated strategies.
- The process of decision-making needs to involve users where there is a solid consensual base, in order to develop a management plan that is both negotiated and technically sound.
- The scientific information that is generated allows a homogenization of the knowledge and understanding of processes that affect ecosystems and that impact on socio-economic and health conditions.
- A consensual agreement has as its objective the design and use of effective methods involving all stakeholders, and the distribution of costs and benefits.
- A framework of inter- and intra-institutional agreements that do not focus on particular interests is

Figure 3.4: Starting from a consensual and inter-disciplinary basis, a multi-institutional course of action and model can be negotiated leading to a consensual process of decision-making for the benefit of all stakeholders. **Source:** Developed by the authors.



sought, as well as general laws that protect society as a whole, in order to guarantee the implementation of plans throughout the decision-making process.

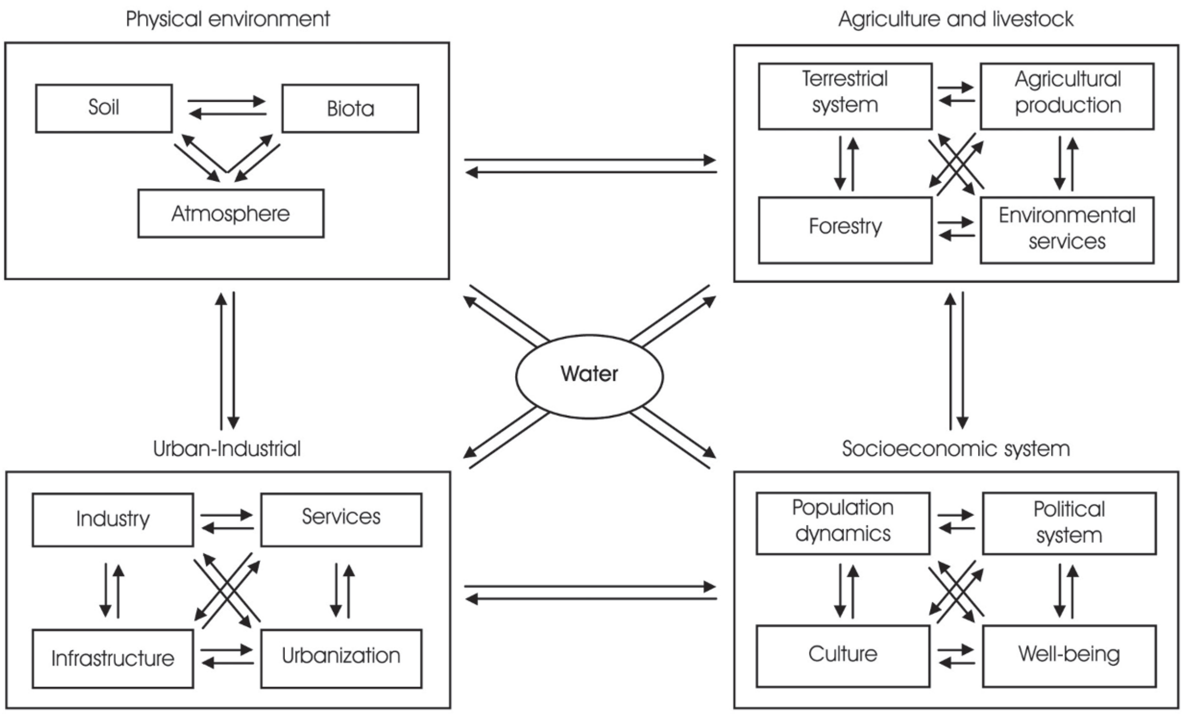
- Finally, it is important to develop a process for evaluating the impacts and effects of the management of the basin that has standard, clearly defined and comparative parameters.

3.3 Conceptual Model

Given the importance of water quality and quantity, an integrated water management approach involves certain processes in the areas of water control or supply of a region. The interrelation of variables that define regional availability and its distinct dimensions must be considered, and an equitable, efficient and sustainable hydraulic administration developed. Figure 3.3 is an example of this interrelationship, showing the cascade effect generated by problems in precipitation in the higher basin (where run-off occurs) down to the lower part of the basin (where most human settlements and irrigation systems are located). It is an example taken from the hydrological region to the north of Mexico (Sánchez, 2007).

Figure 3.3 also shows how hydrological processes are affected by natural and anthropogenic factors. Emphasizing different points in the control matrix allows both problems and also potential solutions to be identified. This matrix constitutes the starting point for development and research projects. A fundamental principle in this model is that any action undertaken in order to mitigate a problem must not have a negative impact, or its consequences should be the minimum possible as far as the entire basin is concerned, both the higher and the lower basin. This is how integrated water management in the hydrological basin is constituted in principle, and it involves a series of repetitive steps that are needed for characterizing the current conditions of the basin, identifying and prioritizing problems, defining management objectives, developing protection or mitigation strategies, and implementing concrete actions (EPA, 2005). Agreed actions should therefore address all these different dimensions and take into account their level of priority (figure 3.4).

Figure 3.5: Structure of an integrated water management model in a basin: dynamic, self-regulated and dissipative system with four subsystems. **Source:** Oswald (2005: 68).



At this point it is important to state that a participatory and multi-objective planning process involves the management of conflicts through a hydrodiplomatic model (Oswald, 2005). Each stakeholder, decision-maker, user or group of users has to defend his or her particular advantage, and there are many competing interests. This leads to obstacles when setting the agenda for the management of natural resources. Only through a rigorous planning process and the negotiation of conflicts and controversies is it possible to reach a compromise (Loucks/Van Beek, 2005).

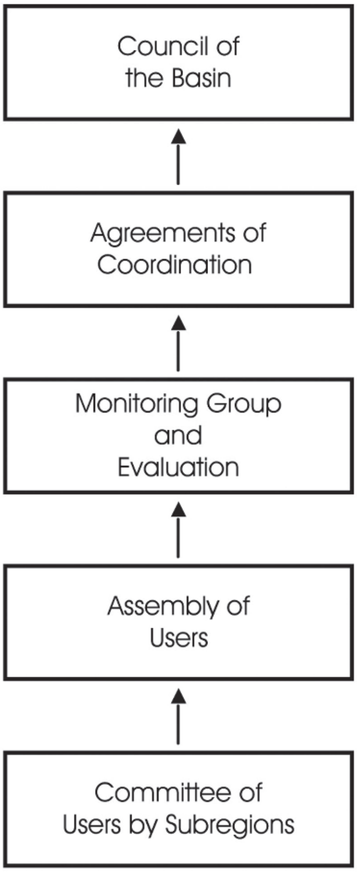
Taking the first step in this direction requires a conceptual model for dealing with the complexity of the interrelationship between water resources and socio-environmental factors. An open, dissipative and self-regulating water system is suggested, with four subsystems: a) a physical environmental subsystem, b) an agricultural subsystem, c) an urban-industrial subsystem, and d) a socio-economic subsystem (figure 3.5). The internal dynamic between these subsystems, what are called the first, second and third level of flows, keeps the system in dynamic equilibrium. That is, the subsystems interrelate through the surrounding conditions at the second level, which in turn may modify their internal dynamic and offer the system certain stability. In the case study presented below the basin is defined as an open or dissipative structure with a dynamic that allows for negotiation and agreement between the different actors and stakeholders in each subsystem, thus leading to an effective decision-making process.

3.3.1 The Institutional Dimension

In an integrated water management model, institutions play a crucial role, as they represent the various interests associated with the use of water resources in a region. Thus, it is important for the authorities managing water basins to take into account the participation of different stakeholders: urban, industrial, agricultural, and public service sectors, without overlooking the requirements of the ecosystem as such. In this field in Mexico the Basin Councils represent the official authority established by the National Water Law (LAN: *Ley de Aguas Nacionales*, CONAGUA, 2004) in order to promote the participation of all parties involved in the formulation, monitoring and updating of water use in each basin in the country. Figure 3.6 offers a conceptual decision-making model within the overall structure of the Basin Councils. In this model, users play a decisive role in the process of reaching common goals and consensus.

Within the technical committees, public servants are also responsible for integrating all background in-

Figure 3.6: Decision-making chart at the basin level. **Source:** CONAGUA (2003: 3).



formation that is useful for validating the users, identifying and defining problems, revealing possible conflicts, mitigating potential adverse effects and suggesting alternatives. Nevertheless, in this model vertical decision-making predominates, and this limits the capacity of the Basin Councils as promoters of participation and democratic decision-making. In addition, confusion is generated between technical issues, socio-political motivations and private interests. This limits the path towards an integrated and sustainable solution.

3.3.2 The Social Dimension

Social well-being is closely related to the availability of water for different uses. Unfortunately, the development model in place in Mexico has generated multiple social tensions and resulted in a population that mostly relies on survival strategies. Thus, the reduction of poverty, the improvement of the quality of life, and equity between people are priorities as far as the conceptualization and planning of water resources and water-related activities are concerned, since they are vital for the protection of the most vulnerable groups. Planning for the distribution of this vital liquid needs to take into account those things that make water a most important factor in the development of rural and urban communities. In addition, water is used for producing energy, for irrigation, for recreational purposes, for industrial use and for many other human activities. Hence, water should be considered as a social and economic good, as noted in the Dublin Statement (GWP, 2000):

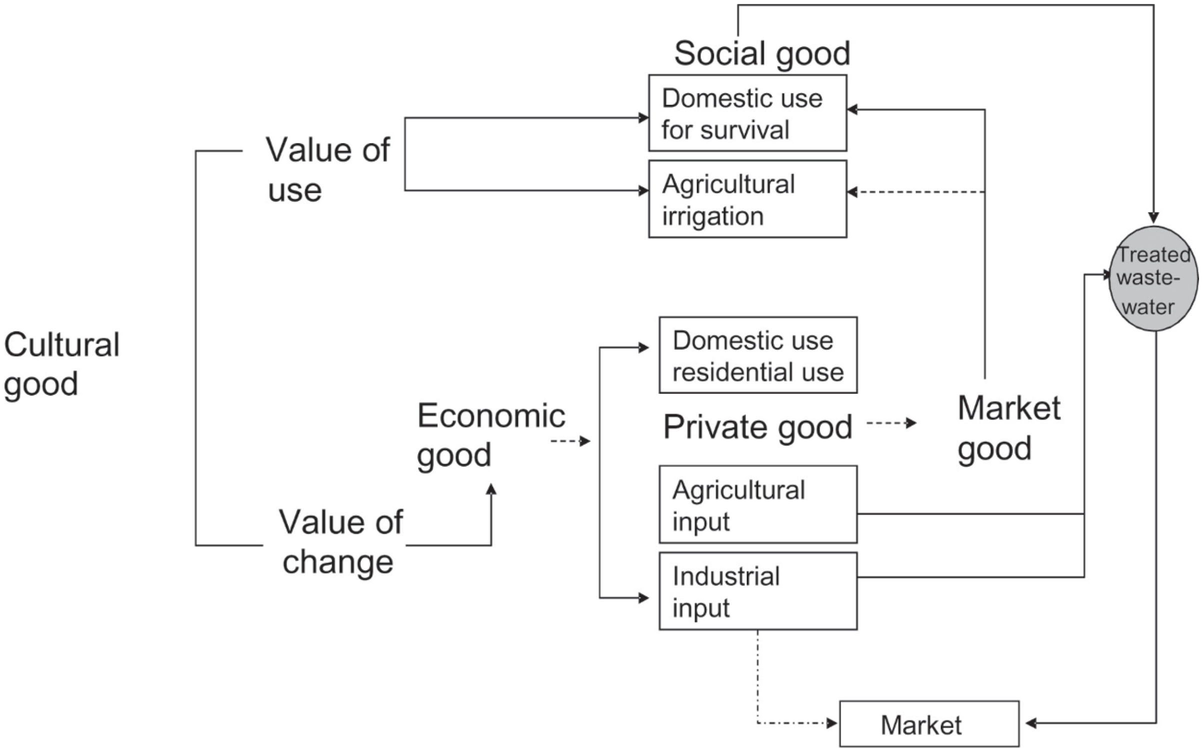
- Water is a finite and vulnerable resource, essential to sustain life, development and the environment.
- Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.
- Women play a central part in the provision, management and safeguarding of water.
- Water has an economic value in all its competing uses and should be recognized as an economic good.

In Mexico payments for water services have been insufficient as they cannot even cover delivery costs. This means that through the government, society subsidizes water services. Unfortunately, with this logic, neither the ecosystem nor the groups that have been taking care of both the ecosystems and water get paid. The situation is exacerbated in the agricultural sector, where efficiency of use is estimated at 40 per cent. Recognizing that water is a natural, social and economic good does not imply that all costs must be covered by the users. The most vulnerable groups in economic terms should have the basic human right to water for their survival; this was one of the controversial points at the World Water Forum in Istanbul (2009), where trans-national water enterprises opposed this minimal right, and was accepted by the General Assembly of the United Nations only in 2010. If it had been accepted, both a social and an economic value would be simultaneously generated by the rules of the water market (figure 3.7).

3.3.3 The Economic Dimension

The price of water is itself an input to productive processes. Nevertheless, its value as a strategic resource has not been clearly defined. Value allocations do take economic and social criteria into account, but they should also account for hierarchies of use such as survival, public health, conservation of ecosystems,

Figure 3.7: Use value and exchange value of water. **Source:** Oswald (2005: 147) modified from Ramos (2004: 101).



and water cycles, and only then productive processes and non-essential uses such as recreational activities. Today, the market controls the value of water, and environmental services appear as fixed tools in decision-making. In Mexico, given that more than 70 per cent of water reserves are used for agriculture, the price users pay for this resource is negligible. Furthermore, within the agricultural sector there are important disparities between big agribusinesses and poor peasants.

Problems in the water sector are linked to low water availability for guaranteeing supply, as well as to lack of funds for financing the operation, management and renovation of hydro-agricultural infrastructure. Given that these aspects are not considered as contributing to the price of water, the existing infrastructure is deteriorating, and the government does not have sufficient resources to maintain or replace it by a more efficient one (IPTRID, 2005).

The mechanisms for setting prices for water in the agricultural sector are varied, and they differ from country to country. In the international arena these mechanisms reflect divergent political objectives, water availability, and a degree of technical development in irrigation, land tenure, crop type, and levels of economic development. In Mexico, water charges are calculated through two main mechanisms: cubic metres and area units. However, payment problems in irrigation districts in Mexico are more related to culture – the belief water need not be paid for – than to users' inability to pay. This presents a complex and unique type of problem, a phenomenon that needs further attention if a sustainable platform with long-term development perspectives is to be developed.

Undoubtedly, agriculture is the main use of water in Mexico. Thus, it is important to consider that, according to projections, climate change will severely impact on rain-fed agricultural lands in dry areas (Sánchez Cohen/Díaz Padilla/Esquivel Arriaga, 2009). This means that considerations of food sovereignty should be added to economic return rates given that there is no worse scenario for a country than to face food shortages and famine; there are many examples which show that conflicts may easily escalate to major conflicts or to regional wars under conditions of hunger (see hunger riots worldwide in 2007/2008).

3.3.4 The Environmental Dimension

Previously it was common practice that remedial or development actions taken at any point in the hydrological basin should have no impact downstream. However, beyond this technocratic outlook, there are some environmental costs that improve social well-being and generate wealth. Technology should account for environmental damage, preserve resources and generate greater productivity for each water drop used (UNESCO, 2005). Pollution of water bodies, environmental costs, and decrease in soil productivity are topics that need to be addressed in order to attain the integrated management of natural resources.

Decisions relating to the implementation of technology should take into account the social, cultural and economic context. It has been shown that in situations where the costs of maintenance, operation or new technology are beyond the capacity of users, services are not sustainable in socio-economic terms, and pollution becomes even greater than before the flawed solution was implemented. This has often been the case with the mismanagement of wastewater treatment plants. Thus, technical solutions have to be designed and selected according to criteria that include efficiency, convenience, cost, and potential for adaptation to local cultural and educational contexts (IPTRID, 2005).

3.3.5 The Political Dimension

One of the most important dimensions of rural change is social participation in debates about courses of action that will lead to sustainable development. Development scenarios should not only take into account biophysical objectives and economic rationality; they need also to take political pressure into account, and this requires an analysis of power balances between most of the political actors involved in rural development. Mexico being a country with an important rural population (23 per cent of the total), its economy is heavily dependent on adequate policies that carry a social impact. The political dimension must consider competence, security, subsidies and pressures stemming from distinct groups, recognizable by competing interests.

3.4 Research Design

Without information about water resources, climatic conditions, and ecosystems, it is impossible to strike an adequate balance between water availability for particular uses. An integrated water balance should take into account water supply relative to demand. Only then can scientifically rooted decisions be put forward in key areas related to water-based policies. Thus, a consolidated knowledge base regarding water resources is a precondition for the development of an effective water policy.

The greatest research challenge in terms of scarce natural resources, specifically in the case of water, is implementing a policy that allows both for economic development and sustainability (Oswald, 2003). Disentangling the complex linkage between water, other resources, and socio-economic and political processes, it is crucial to understand the impact of environmental changes given any construction works that may alter the basin. Clearly defined environmental impacts provide useful tools to decision-makers, and also endow responsible parties with simple and trustworthy instruments for water management.

Of course, in the bigger picture water users are also included, even if higher payments are periodically demanded from them. Nevertheless, as has been previously noted, the cost and value that is given to water in Mexico comes nowhere close to political discourses that frame water as a "national security resource"[1]. Science is still seeking methods to link the sustainability of this natural resource with economic growth in order to make environmental conservation appealing. The challenge is to address real water costs given the use and abuse of natural resources; and for this, scientists need to be included in national development plans and in the creation of conservation norms and regulations, in order to establish a strict and realistic legal framework that includes social participation.

For integrated management of water resources, a hydrological balance is the axis of planning (Arreguín/Alcocer, 2003). However, understanding the water cycle in an integrated fashion is no easy task; thus, research should account for the following considerations.

3.4.1 Scientific Considerations

The following scientific considerations should be taken into account:

1 This vision of national security is tied to the narrow Hobbesian definition of military and political security. It does not take into account the new definitions of water security developed at the second World Water Forum in The Hague (Oswald/Brauch, 2009a and 2009 b), where ministers from participating countries included social, environmental, political, equity and differential water use components, as well as stressing access to water as a first generation human right.

- All components of the water cycle should be analysed, including the vertical and horizontal dimensions and the interaction between surface and groundwater and the role of vegetation and soil in this process.
- A correspondence between time and space series should be established for each component of the water cycle.
- The specific spatial representation associated with each component of the water cycle should be established. This implies changing the scale of analysis from the parcel of land, district or region to the basin in order to account for natural and anthropogenic differences in kind of space.
- The interaction of the water, carbon, nitrogen and other cycles should be quantified, to include environmental services, agricultural production, and urban-industrial and recreational uses.

3.4.2 Social Considerations

The following social considerations should be taken into account:

- It is necessary to investigate whether traditional rights of water and land use are in conflict with the objectives of the projects. In Mexico it is especially important to take land tenure into account, given that any initiative that contravenes the legal framework and the traditional 'uses and customs' system will find serious barriers to implementation. However, research should also provide decision-making tools that allow updating of laws and inclusion of traditional practices in the development processes.
- It should further be considered whether the outcomes of the project will encourage either population displacement or unregulated migration or both, and whether water markets will increase social inequalities. Also, generalized access to the benefits of the project should be guaranteed, and socially vulnerable groups should be especially protected.

3.4.3 Economic Considerations

The following economic considerations should be taken into account:

- Not only should the cost-benefit relations of proposals be analysed in monetary terms, but also the socio-cultural impacts and sustainability of natural resources should be considered.
- Opportunities in the hydrological gradient for increasing water productivity and savings should be identified, and recycling and reuse of water in other productive cycles should be encouraged to avoid pollution.
- Enough information should be generated to design tariff incentives (including subsidies, taxes and exemptions) and to offer the necessary technologies and systems to monitor water use efficiency.
- Information should be developed that sustains economic charges for water services as direct payments or as compensation for environmental services.
- Indicators for the evaluation of the economic impact in different social groups should be specified and required data should be collected for each social stratum to develop these indicators.

3.4.4 Cultural Considerations

In the development of a new culture of water use this premise needs to be addressed: if the objectives of the management of water resources are not understood it will be impossible to get users to participate in the planning and development of activities, much less in the processes of decision-making and in quantifying their water needs. Thus, the most important considerations are:

- Special attention should be given to persuade stakeholders to share the benefits of the project with the most vulnerable groups, to care for environmental and human health, and to analyse alternative sources of water and sanitation. Generally speaking, water demand in marginal communities is linked to their survival (Oswald 1991, 2008). Thus, research should consider both mixed and multi-purpose low-cost technologies.
- Given the current gender balance in terms of water users, the project should consider the involvement of women as essential in the decision-making process.
- Given ancestral cultural habits – especially among the most vulnerable groups – it is crucial for project promoters not to try to or abruptly change traditional attitudes. Instead, they should aim at optimizing aspects that improve productive and water management systems in order to gradually implement necessary changes for improving living conditions among these marginal populations.

3.5 Conclusions

The international framework for water resource management across different nations is increasingly oriented towards integrated water management. This is quite clear in the manifesto that was adopted at the Fourth World Water Forum celebrated in Mexico in March 2006. Furthermore, the Fifth World Water Forum in Istanbul in March 2009 focused on the impact of climate change on water quality and availability. Thus, the development of research needs must include both, in order to offer effective solutions to the multiple challenges faced by our nation. This multi-objective and multidisciplinary vision should always be present in large scale projects. It should not be forgotten that integrated water management implies the interrelationship of subsystems: environmental, agricultural, urban-industrial, and socio-economic-political; each with a distinct agenda, different rhythms and different spatial scales. For this reason, global vision often requires local actions (Sánchez/Macías/Catalán, 2006). This vision seeks to solve knowledge gaps in a complex problem matrix where every region and hydrological basin is different. Nevertheless, the participatory research-action approach is presented for this scenario, accounting for all actors involved, and obliging governments to develop policies based on their demands.

It is important to gear actions towards parallel objectives, instead of establishing hierarchies. Thus, independence between objectives at each stage of the integrated management project allows users and stakeholders to accept such objectives. This means generating sources of funding for different interests, but within a master plan that integrates all the objectives and targets. Breaking up objectives to a smaller scale will help funding requirements as well as generating the necessary conditions for users to pay, by providing them with quality services that are environmentally friendly. It is also important to emphasize that the time scale of a project of great vision transcends a particular six-year term of office (Villanueva/Stahle/Cerano et al., 2006); it requires planning ahead for three to five decades. However, it is still possible to break up particular objectives and to 'deliver' and solve emerging problems in the short term. Sustainability of water resources is not an end to be achieved; it is rather a process, a work-in-progress with periodic and thorough adjustments.

Finally, water research should become a state priority and should also be granted sufficient funding. This also applies to research on sustainability, which should not be neglected because of lack of resources. Water is a common good of primordial importance, as well as a basic need for human and environmental survival. Water scarcity affects life and health, and any responsible government should carry out its duty to provide its citizens with clean water. Citizens are human beings with basic needs. Furthermore, a lack of water as well as pollution and its monopolization affect food production – traded food is also called virtual water (Allen, 2001). Instead, water can offer nourishment, development, prosperity, peace and order for all social sectors. The integrated management of water requires the application of knowledge from many different disciplines if it is to provide innovative solutions; indeed, science and technology are the basis of the integrated management of resources.

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4 Analysis of Weather Time Series for Decision-making in Mexico

Gabriel Díaz Padilla, Ignacio Sánchez Cohen and Rafael Alberto Guajardo Panes

4.1 Introduction[1]

The analysis of time series in weather variables principally involves three mathematical-statistical processes: a) the development of a qualified database without erroneous data or missing information; b) fitting the data to a theoretical statistical distribution; and c) the assessment of spatial interpolating techniques. For this analysis, 2165 weather stations in Mexico with daily rainfall records were chosen, taken from the network of weather stations of the National Weather Service.

To meet this goal, the following criteria were used: a) weather stations with at least 20 year-old records, b) 75 per cent of records taken between 1961 and 2003; and c) the weather stations had not suspended their work before 1993. The first step of this analysis entailed the utilization of a widely used computer program known as R-ClimDex, with which it was possible to verify the quality of data through tabular and graphic reports provided within the program. The missing records were generated through another commonly used program called ClimGen (an ideal one for this task, after several weather generators had been evaluated by Wilcoxon and Friedman non-parametrical tests). The databases with complete and good-quality information were integrated into the *Query System and Weather Information Processing in Mexico* (SICLIMA).

To assess how well these data fit the gamma distribution, two periods were analysed: a) from May to October, when 80 per cent of the rainfall in Mexico occurs, and b) yearly. Through re-sampling techniques (bootstrap), we calculated the Anderson-Darling test, and the shape (α) and scale (β) parameters of the distribution. We found that 78 per cent of the analysed weather stations for the period from May to October, and that 83 per cent of the yearly period adjusted to a gamma distribution with average values of α=19,68 and β=55,40, and of α=17,58 and β=56,30 respectively.

With regard to the spatial interpolation, the following methods were compared through the *Mean Square Error* (MSE): *Inverse Distance Weighted* (IDW), Kriging, Co-kriging and Thin Plate Smoothing Spline (TPSS). To do so, we needed to use the historical information records of rainfall corresponding to the month of September in 147 weather stations in the windward and leeward regions of the Gulf of Mexico.

The surface generated by the TPSS method was found to be the best for recording the smallest MSE prediction, followed by the Kriging, Co-kriging method (Gaussiano Model); and Inverse Distance Weighted with an optimized value. Finally, based on previous outcomes, spatio-temporal maps of monthly, yearly and May-October period rainfall were generated; as well as national maps for parameters α and β corresponding to the gamma distribution, considered very useful in the spatial regionalization of rainfall in Mexico to probabilities of 70, 80 and 90 per cent.

To assess availability or regional climatic limitations efficiently, it is necesary to define the quantitative weather elements, especially temperature, rainfall, environmental humidity, evaporation, solar radiation and wind, among others (Villalpando et al., 1991). This requires representative and reliable climatic information in a database with high-quality records that are as recent and complete as possible, to support the investigation areas of planning, agriculture, livestock and forestry. It should also cover any other expected applications, and function as a support tool for other areas of knowledge, based on standarized information from any period.

Despite the importance of climatic information, only a few attempts to update it have been undertaken during the past 30 years. Its significance has been considerable, however; the need to rely on updated information has furthered the development of databases and climatic information systems at national and state level, as García (1975), and Medina et al. (1994) have

1 Key words: rainfall, gamma, interpolation; lines of research: climatic and geo-statistical modelling.

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_4,

done for the Republic of Mexico, Villalpando and García (1993), Flores (1994), Ruiz et al. (2000a, 2000b) for the State of Jalisco, and Alcántar et al. (1999) for Michoacan.

By the late 1990s, several databases were compiled throughout the country concerning the weather, most of them on hard disc such as ERIC I and ERIC II. Because of their smooth distribution, these data were intensively used by the community as a source of climatic information up to the year 2002; and to this date, they are the only known data source for some investigators and user institutions (Vazquez, 2006). With this in mind, our goal is to present an approach to shaping a database totally debugged of atypical records, to detect periods of missing information and then, to calculate these through a generator of climatic information.

4.2 Objectives

4.2.1 General Objective

The general objective has been to develop a methodology that allows us to carry out the analysis of weather time series for decision making purposes in Mexico.

4.2.2 Specific Objectives

Among the specific objectives have been:

a.) to have the database debugged of atypical records;
b.) to calculate, through a generator of climatic data, the missing values of rainfall as well as the maximum and minimum temperature;
c.) to develop a system that permits the handling of climatic information for processing statistics and interest indicators;
d.) to evaluate methods of interpolation that will best represent the conditions and characteristics of the different regions in the country;
e.) to generate continuous surfaces for rainfall, maximum and minimum temperature;
f.) to quantify and define the spatio-temporal distribution of rainfall;
g.) to calculate the shape and scale parameters of the gamma distribution;
h.) to interpolate shape and scale parameters in a national level;
i.) to create rainfall maps that achieve probabilities of 70, 80 and 90 per cent.

4.3 Methodology

4.3.1 Source of Data

To carry out this work, is was necessary to use information from the *National Weather Service* (SMN), an organization in charge of gathering and analysing the daily climatic information, which is collected in a national database (figure 4.1). These data are the daily records of rainfall, of the lowest and highest temperature, and evaporation, from 5088 weather stations that belong to the network of meteorological monitoring of the *National Water Commission* (CONAGUA) in Mexico.

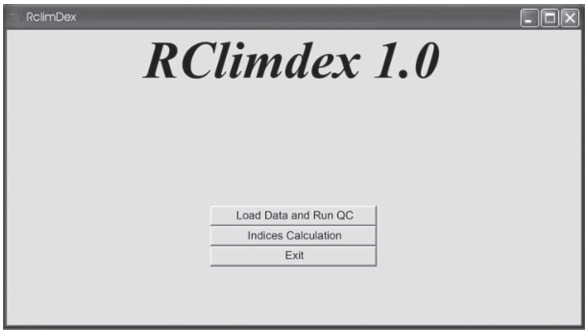
4.3.2 Selection Criteria for Stations

This information was incorporated into an Excel spreadsheet and it was revised with the aim of identifying the stations that had at least 20 years of information, where 75 per cent of it was within the period 1961 to 2003, and that had not suspended their work before the year 1990.

4.3.3 Verifying the Quality of Data

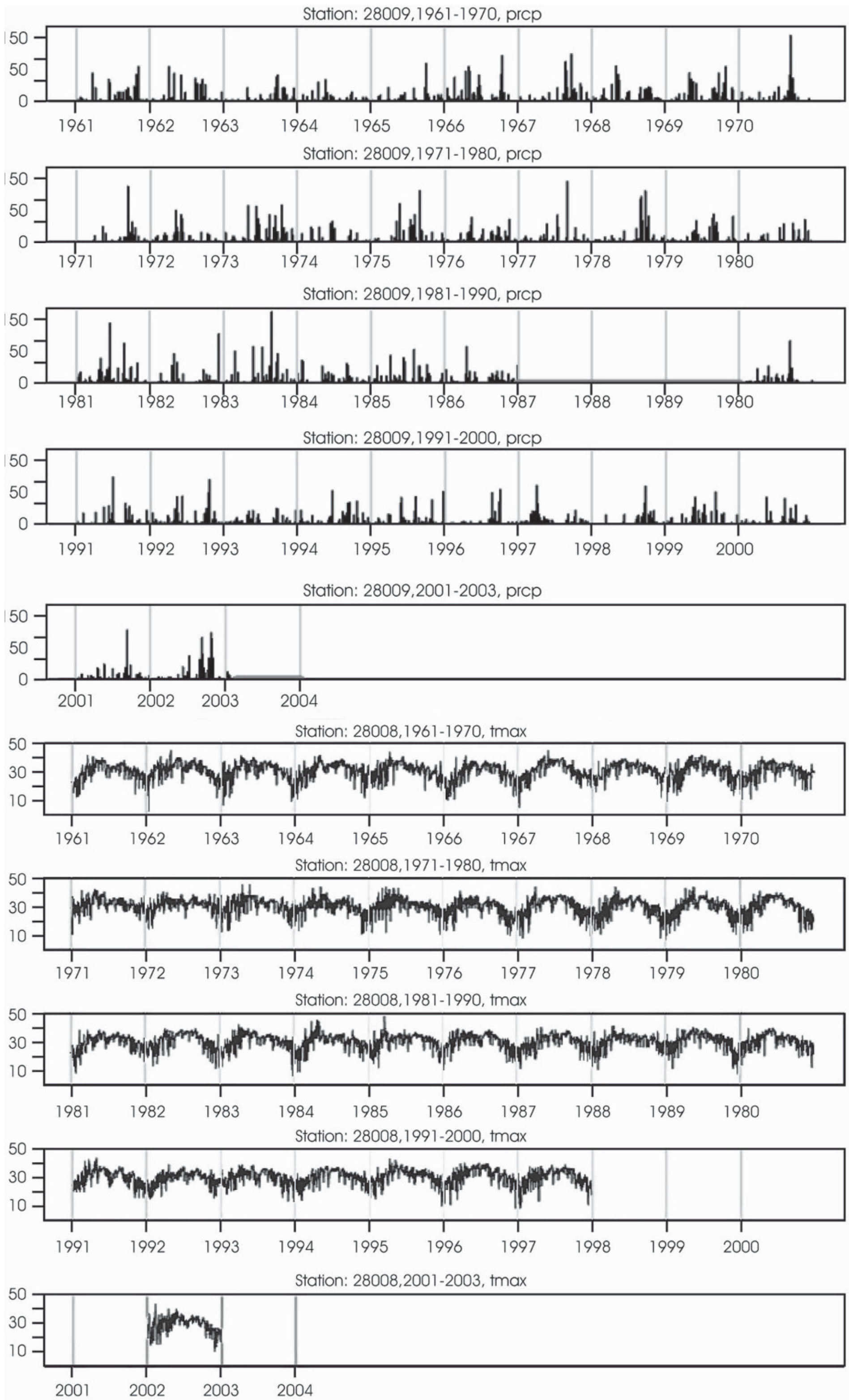
Later, using the program R-ClimDex (Zhang/Yang 2004), it was possible to identify and eliminate those records with daily rainfall data below zero, data for the maximum daily temperature and the minimun temperature, the data from 29th February when it was not a leap year, and on the 31st day of months with only 30 days.

Figure 4.1: Start-up panel of the R-ClimDex 1.0 program. **Source:** Zhang/Yang (2004).



This program offers a graphic interface for visually exploring the behaviour of different rainfall variables, as well as of the maximum and minimum temperature (figure 4.2).

Figure 4.2: Display of climatic series in R-ClimDex. **Source:** Research data based on information provided by the National Weather Service and CONAGUA.



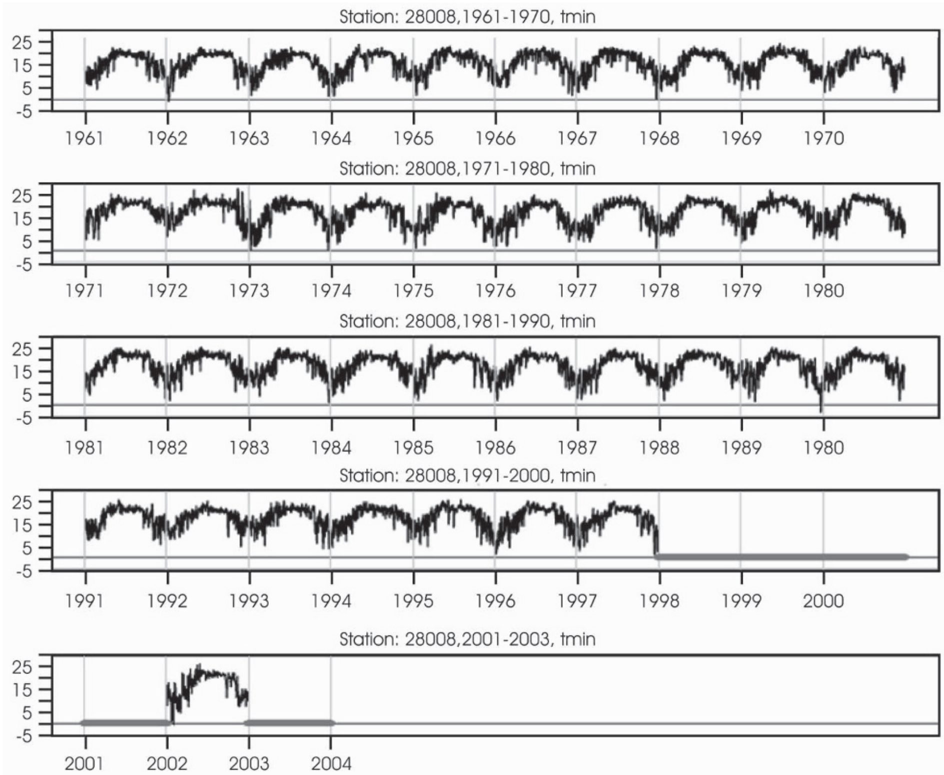
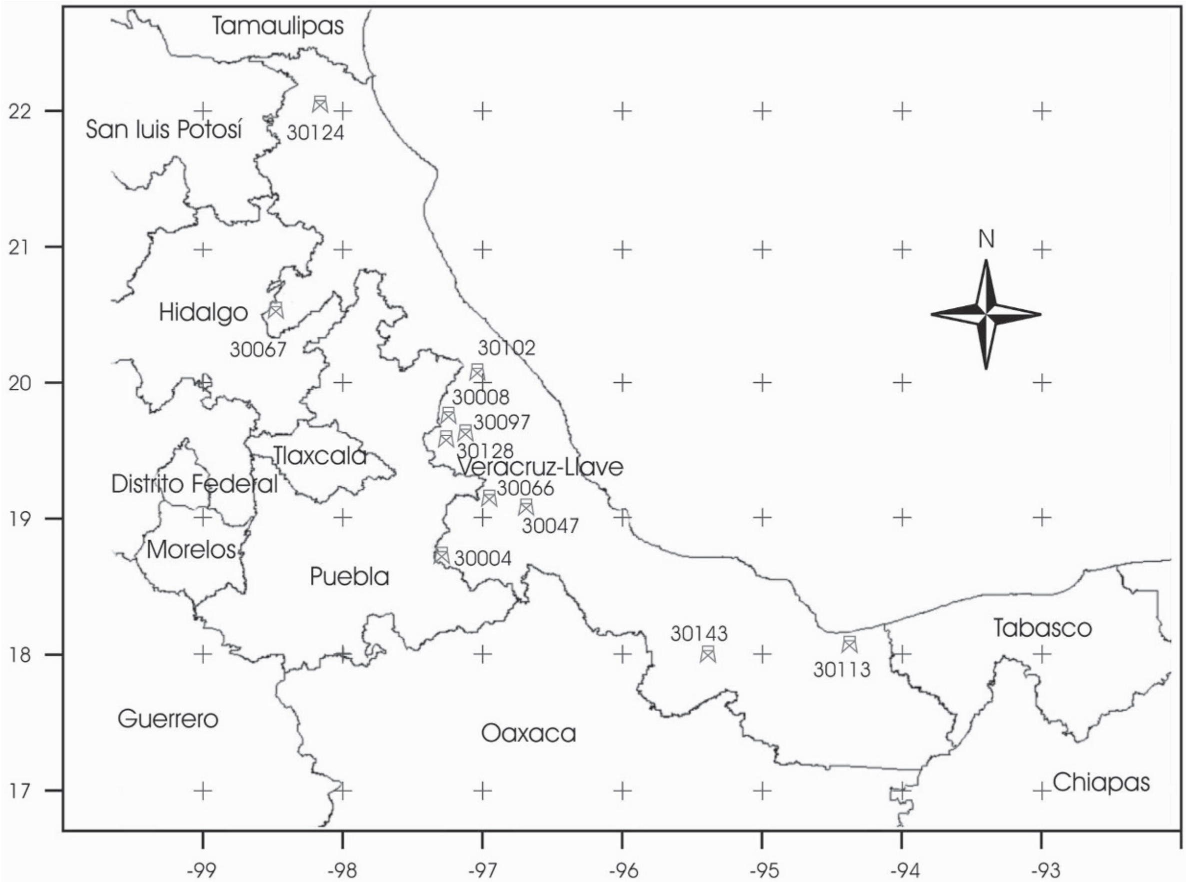


Figure 4.3: Tabular reports of inconsistencies in the climatic database. **Source:** Authors' research data.

year	month	day	prcp	tmax	tmin	tmax-tmin
1966	11	27	0	23	23	0
1986	12	10	9.5	12	12	0
1999	12	23	20	8	8	0

year	month	day	prcp	tmax	tmin
1961	1	30	-1.0	0	19.0
1961	12	24	-1.5	4.5	30.0
1962	12	28	-0.5	4.0	11.5
1962	1	2	-0.5	2.5	10.5
1962	1	8	-0.3	-0.3	16.0
1962	1	7	-0.2	6.0	24.0
1962	1	8	-0.1	1.5	24.5
1962	1	10	-0.4	-0.3	6.0
1962	1	11	-0.6	-0.4	2.0
1962	1	13	-1.1	-0.7	5.0
1962	1	13	-0.9	1.5	23.0
1962	1	20	-0.5	2.0	21.5
1962	1	29	-0.5	3.0	22.0
1962	1	30	-1.5	3.0	23.5
1962	1	31	-0.5	2.5	25.0
1962	3	2	-0.5	1.5	22.0
1962	3	16	-0.2	3.0	9.5

Figure 4.4: Chosen stations for the State of Veracruz. **Source:** Authors' research data.



This program also allows us to verify tabular reports of inconsistencies in the climatic variables, such as the ones shown in figure 4.3.

Once the quality and coherency of the information has been revised, the records with missing information were calculated with a climatic generator.

4.3.4 Choosing the Right Climatic Generator

A weather generator is a stochastic numerical model to generate daily weather series statistically identical to the observed ones. It can be used to generate long time-series of weather, suitable for risk assessment. It provides the means of extending the simulation of weather to unobserved locations; to serve as a computationally inexpensive tool to produce climate change scenarios incorporating changes in climatic variability (Semenov/Barrow, 1997). In agricultural investigation, it is essential to count on complete climatic information, but this usually presents a problem; and that is why climatic generators become a feasible option that enables us to fill in unregistered information in a series of rainfall, maximum temperature and/or minimun temperature values. Today, a great number of computer programs that generate climatic data have been developed; thus, it was necessary to implement a statistical test that could make it possible to determine which of them might offer the closest approximation to real records.

To conduct the comparison testing between climatic generators, a station sampling process was needed, which helped provide a reference for what happens in all of them. The sampling process that was used was a simple random one. A sample is called simple random sample (SRS) if each unit of the population has an equal chance of being selected for the sample. Whenever a unit is selected for the sample, the units of the population are equally likely to be selected (Schaeffer et al., 1994). The equation that was used to calculate the size of the sample was as follows:

$$n = \frac{N\sigma^2}{(N-1)D + \sigma^2} \qquad 1)$$

Table 4.1: Description of stations that were considered in the sampling. **Source:** Authors' research data.

Station code	Station name	Weather	Latitude	Longitude	Altitude (m)	Observation period
21040	Guadalupe, Buenavista	Dry	-97°21′36″	19°22′33″	2,407	1961-1988
30128	Perote, Perote	Dry	-97°16′01″	19°34′59″	2,329	1965-1997
30004	Acultzingo, Acultzingo	Warm	-97°18′00″	18°43′01″	1660	1961-1980
30008	Altotonga, Altotonga	Warm	-97°15′00″	19°45′00″	1899	1961-1991 1993-1997
30066	Huatusco de Chicuellar	Warm	-96°57′00″	19°09′00″	1198	1961-1990 1992-1997
30067	Huayacocotla	Warm	-98°28′59″	20°31′58″	2100	1961-1989
30097	Los pescados, Perote	Warm	-97°07′59″	19°35′59″	2,518	1964-1997
30047	El Coyol, Comapa	Rainy	-96°42′00″	19°07′11″	610	1964-1997
30102	Martínez de la Torre	Rainy	-97°03′00″	20°04′01″	85	1961-1997
30113	Nanchital	Rainy	-94°22′59″	18°04′01″	16	1960-1983
30124	Pánuco, Pánuco	Rainy	-98°10′01″	22°03′00″	9	1961-1988
30143	Juan Rodríguez Clara	Rainy	-95°24′00″	18°00′00″	113	1961-1984 1993-1997

With

$$D = \frac{B^2}{4} \qquad 2)$$

where N is the size of the population, σ^2 represents the population variance of the variable of interest, B is the margin of error for the estimate (usually 5 per cent), D corresponds to the quotient of the margin of error for the estimate squared to the value in the corresponding Z-score Table at a 95 per cent confidence level (1.96) which is rounded up to two and squared, and n is equal to the size of the sample.

Since the stations are located in regions with heterogeneous meteorological conditions, a geographic area with climatic diversity was considered in order to observe whether the results of the generated missing information were congruent with the location of the source station.

For all this, we considered working with information from stations placed throughout the State of Veracruz, due to the varying climatic conditions that prevail in that state. The size of the sample was established in twelve stations that were chosen at random, and the comparative analysis was made based on the variable of rainfall. The geographic distribution of the meteorological stations is shown in figure 4.4.

The selected station are listed in the table 4.1, as well as their geographic location and predominant weather.

It is of utmost importance that the generation of climatic information be as close as possible to what happens in real situations. To do so, we drew on information that was recorded during the operation of the weather station within different periods of days. To achieve this, it was necessary to select data groups from different times, based on random sampling schematics, so that the information selected could truthfully represent the series of observed data. The process for the selection of the data groups was as follows:

a.) All records with complete information for the variables of rainfall and maximum and minimum temperature from each station were accounted for; and those with missing data, in any of these variables, were eliminated.
b.) The total number of groups with continuous series of information within periods of 5, 10, 15 and 30 days was accounted for, for each of the stations.
c.) Five sampling sizes (one per series) were estimated, so that later on we could select the elements of the sample through random sampling.

With this process, it was possible to confirm, through statistical hypothesis tests, if there was a significant difference between the real values of rainfall and those generated by the routines included in the programs ClimGen (Nelson, 2003) and Lars-WG (Semenov/Barrow, 1997).

4.4 Hypotheses

The hypotheses to be proven are:
H_0: there are no differences between the observed values of rainfall and those generated by ClimGen and Lars-WG.
versus
H_1: there are differences between the observed values of rainfall and some of those generated by ClimGen and Lars-WG.

To prove these hypotheses, there are two methods:

a.) parametric tests that are an inference method, related to the estimation and verification of the hypothesis concerning the population parameter; and
b.) The non-parametric tests are an appropriate method when the minimun assumptions of application are not met for a parametric procedure (independence, normality, homogeneity of variance, etc.), or do not refer to population parameters (Ramírez/López, 1993).

With all this in mind, and with the awareness that the rainfall data differ from a normal distribution, the hypotheses were contrasted with the non-parametric methods of Wilcoxon and Friedman, since they allowed for the detection of differences between the observed data and those generated for each one of the series of information within the previously established periods.

With the Wilcoxon test, it is possible to carry out the analysis on three pairs of data; that is to say, we contrasted the possible combinations of the three sources of information. On the other hand, the Friedman test permitted a multiple simultaneous comparison between the original data, those generated by the Lars-WG, and those generated by ClimGen.

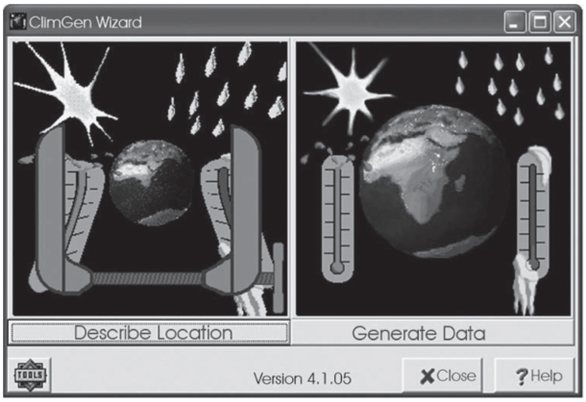
The data were processed with the STATISTICA 7.1 program, using its non-parametrical module, which, when analysing the information, produces a value P or a significance value that can be used as an index of the testing force of the data against *Ho*, that is, the lower the value of P, the greater the power of evidence against the null hypothesis (Abraira, 2002).

4.5 Data Management

4.5.1 Generation of Missing Values

Once the quality and coherency of the missing values have been revised, the missing data for rainfall and maximum and minimum temperature were estimated using the ClimGen program (figure 4.5). This program requires a file for each year of information, and the missing data must be recorded with a value of -9999. The records with information are processed and analysed, and based on them, the necessary parameters are calculated to generate data for rainfall and temperature.

Figure 4.5: Start-up panel of the ClimGen program 4.1.05. **Source:** Authors' research data.

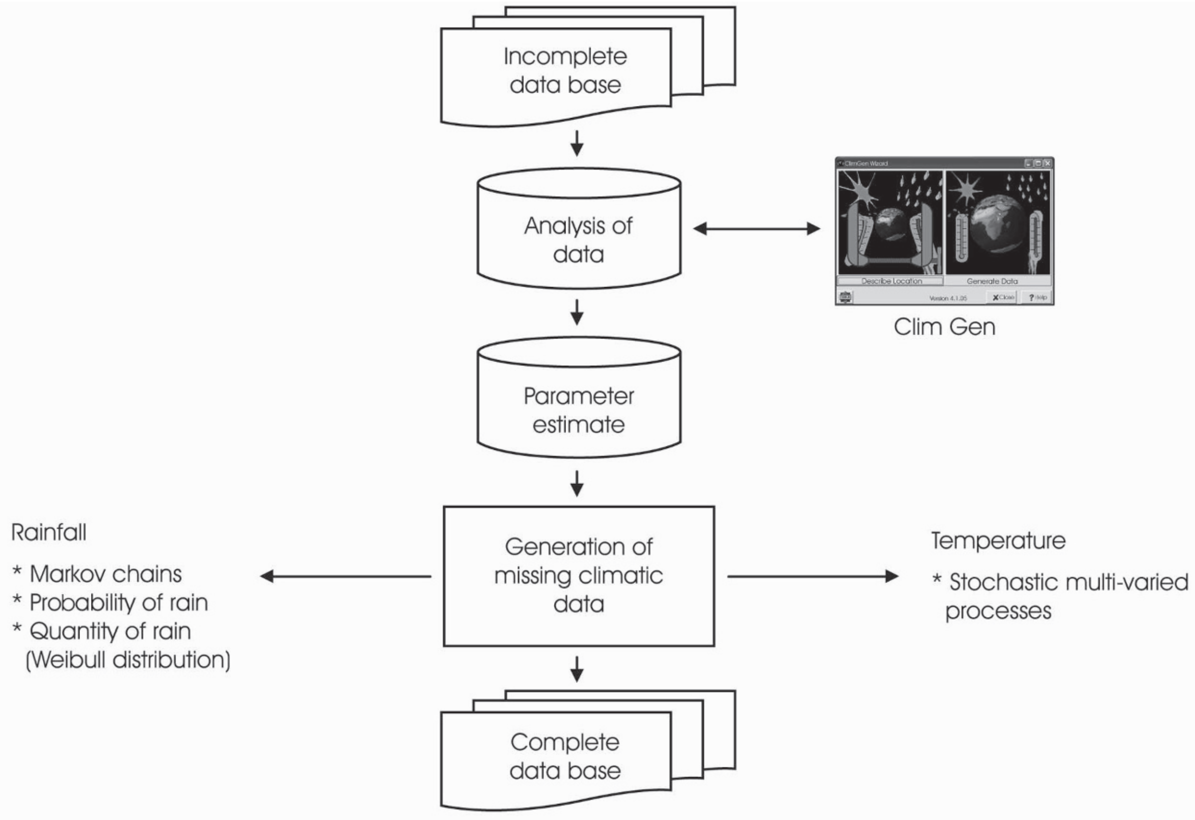


The daily temperature data are generated through the process of interpolation, using a quadratic model called 'Spline', without having to use a radiation variable, nor go through periodical regressions. It is assumed that the temperature is a weak and stationary process (Matalas, 1967). Therefore, we considered that both the maximum and minimum temperatures are a continuous and stochastic process with daily means readings and standard deviations, conditioned by the daily status of rainfall (humid or dry) (Richardson, 1981).

The time series of residual elements, as well as that of both the maximum and minimum temperature temperatures, are obtained by removing the periodical means readings, and the periodical rising of standard deviations. So, the elements are analysed for their independence of time and cross-correlation.

Nevertheless, the rainfall data are generated using Markov chains to determine the occurrence of rainfall; and using the Weibull function, we calculated the quantity of rain that could have fallen. One of the

Figure 4.6: Process of generating information. **Source:** Authors' research data.



advantages that this software offers is the possibility of keeping the original values and only substituting the records with a generated value where there is something missing (-9999). Figure 4.6 shows the process of data generation.

Once the process is completed, the data are exported into an Excel spreadsheet so as to have a complete series of information for each one of the 2,271 stations distributed throughout the country, and to make it easy to export them into a Data Base File (DBF), which further simplify the processes of climatic information.

4.5.2 Processing of Climatic Information

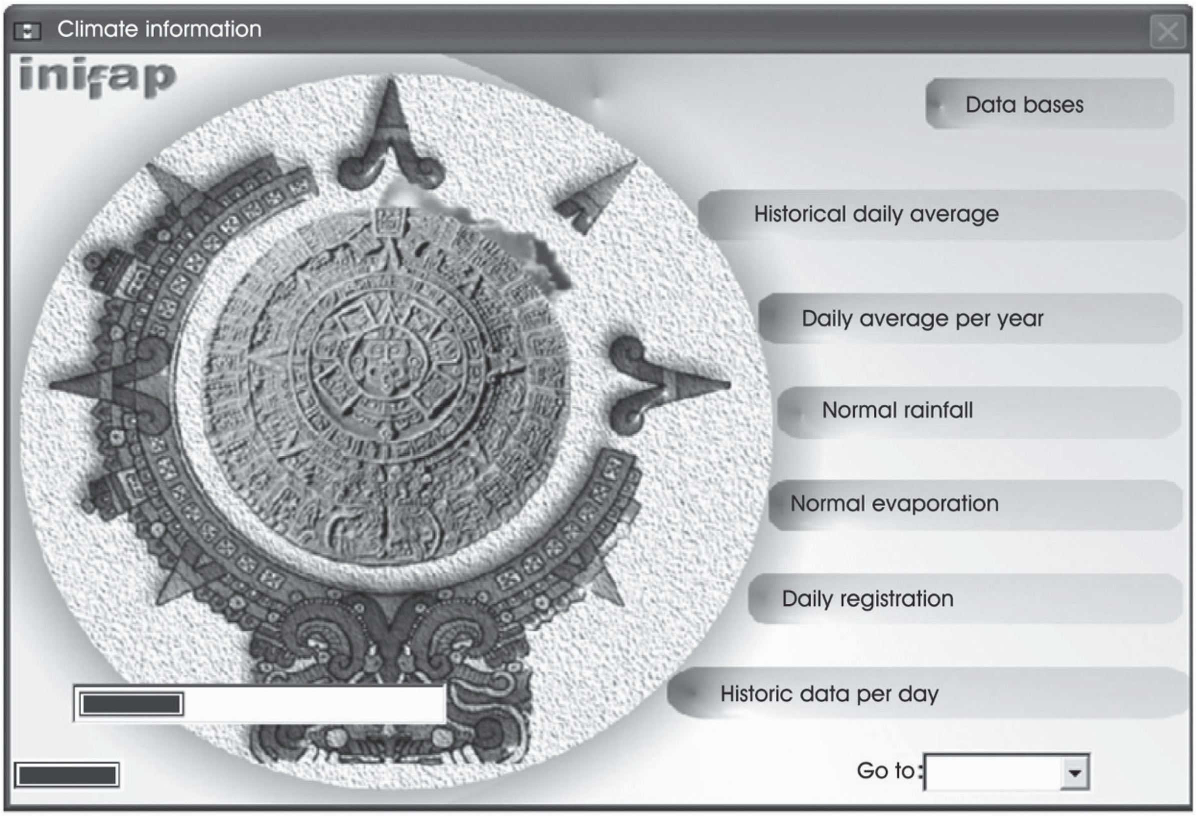
As part of the investigation of climatic information in the National Institute for Forestry, Agriculture and Livestock Research of Mexico (INIFAP), it was crucial to have an automated tool that would allow for the processing and analysis of information within different periods of time (daily, monthly, yearly and historical), in a friendly computer environment that would integrate the graphic visualization modules of the data in each of the weather stations spread all around the country.

Diaz and Cortina (2005) developed a system with specific functions distributed in different modules, whose purpose is to process the climatic information contained in the files in DBF format, called *Query System and Weather Information Processing in Mexico* (SICLIMA) whose start-up layers are displayed in figure 4.7.

4.5.3 Estimate of Density Function of Gamma Distribution

The statistical distribution of the many atmospheric variables is clearly asymmetrical and skewed to the right (Wilks, 1995). Some common examples of this are the quantity of rainfall that occurs in a specific place, and wind speed. Adjusting these variables to distributions such as the Gauss curve might produce wrong results by modelling or quantifying a certain probability of occurrence. As has been previously stated, the continuous distribution that has been observed to match the rainfall data is the gamma distribution. It was probably Barger and Thom (1949) who made a point of using the function of the gamma distribution to represent rain data.

Figure 4.7: Start-up Panel for Query System and Weather Information Processing in Mexico (SICLIMA). **Source:** Authors' research data.



The gamma distribution is defined by the function of the probability distribution:

$$f(x)=\frac{(x/\beta)^{\alpha-1}e^{\left(-\frac{x}{\beta}\right)}}{\beta\,\Gamma(\alpha)} \quad x,\alpha,\beta>0 \qquad 3)$$

where X is the value of the observed rainfall and the α and β values are the parameters of distribution shape and scale. The function Γ (α) is defined by the integral:

$$\Gamma(\alpha)=\int_0^{\infty} t^{\alpha-1}e^{-t}\partial t \qquad 4)$$

This must be evaluated numerically and/or approximated using tabular values provided in the table of Wilks (1995) and Sánchez et al. (2008).

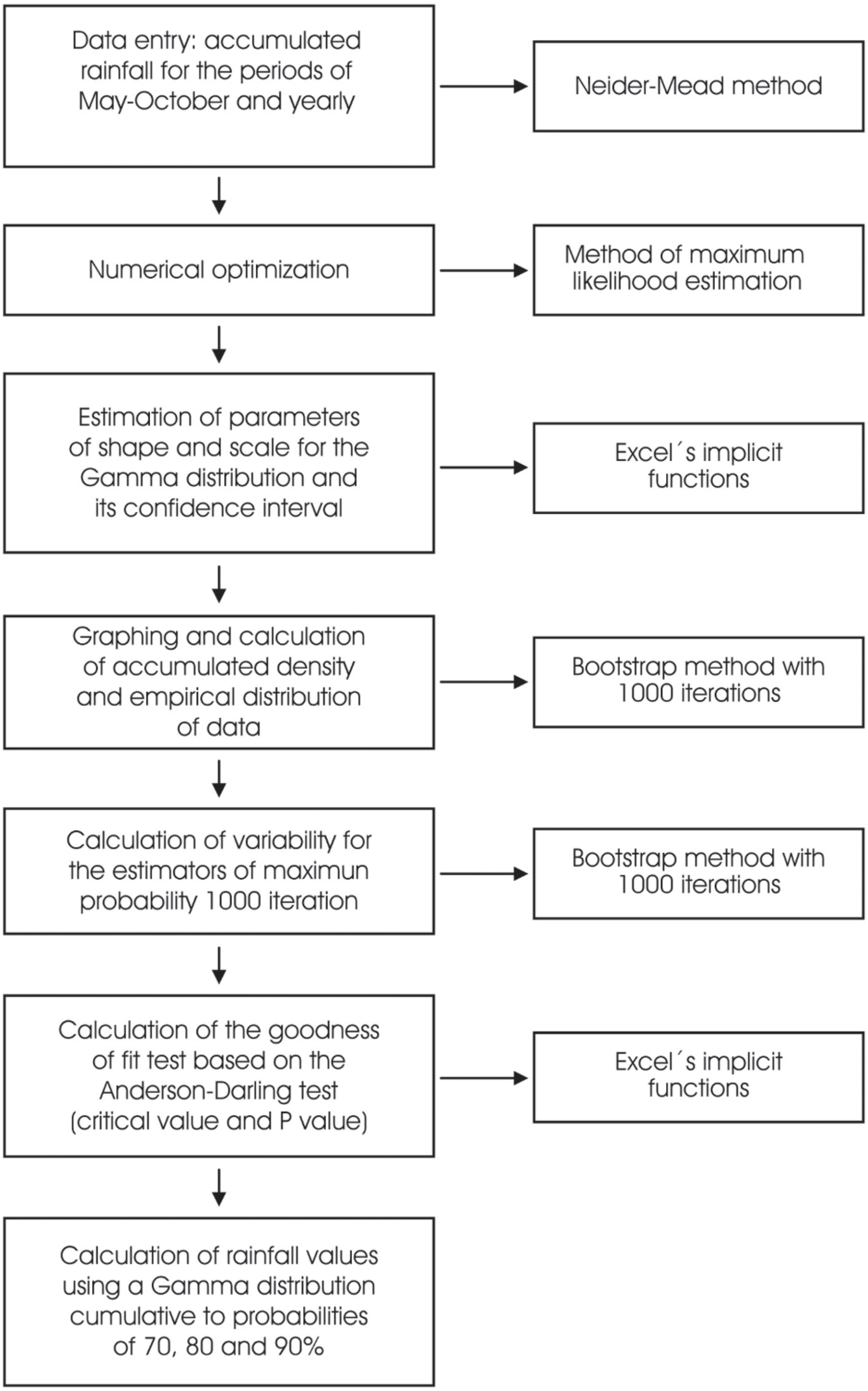
One problem of the gamma distribution is the estimation of its parameters; several authors propose different ways of estimating them, and one of the best is that of maximum probability, which requires an iterative process that is only practicable with the use of computers. Wilks (1995) describes the approximations for this purpose, the first of which is pointed out by Thom (1958); and the second one is a polynomial approximation for the α parameter proposed by Greenwood and Durand (1960).

To a large extent the analysis performed in this project is based on the work of Cheng (2006), who developed a series of algorithms and programs in Visual Basic incorporated in a spreadsheet. Using all this, it was possible to calculate the shape (α) and scale (β) parameters of the gamma distribution, its confidence intervals, accumulated functions, empirical and probability distribution by applying the method of *maximum likelihood estimation* (MLE), so that we could finally carry out the matching test by 'bootstrap' resampling, utilizing the Anderson-Darling test with its corresponding critical value and the value P. The process that was used is summarized in figure 4.8.

4.5.4 Evaluation of Interpolation Methods

The interpolation methods to be evaluated were Inverse Distance Weighted, Kriging and Co-Kriging, and Thin Plate Smoothing Spline. The testing region

Figure 4.8: Methodological process for calculating the matching of the gamma distribution with the historical series of rainfall in the Republic of Mexico. **Source:** Adapted from Cheng (2006).



comprises a portion of the Republic of Mexico located in the area of windward and leeward between 19°55’48” and 18°47’24” northern latitude and 99°09’00” and 96°03’36” eastern longitude, showing the pronounced influence from the Gulf of Mexico and the pressure, atmospheric and temperature conditions from the Atlantic Ocean, which makes this region characteristic for the behaviour of the weather.

Figure 4.9: Spatial distribution of 147 stations in the windward and leeward areas of the Gulf of Mexico. **Source:** Authors' research data.

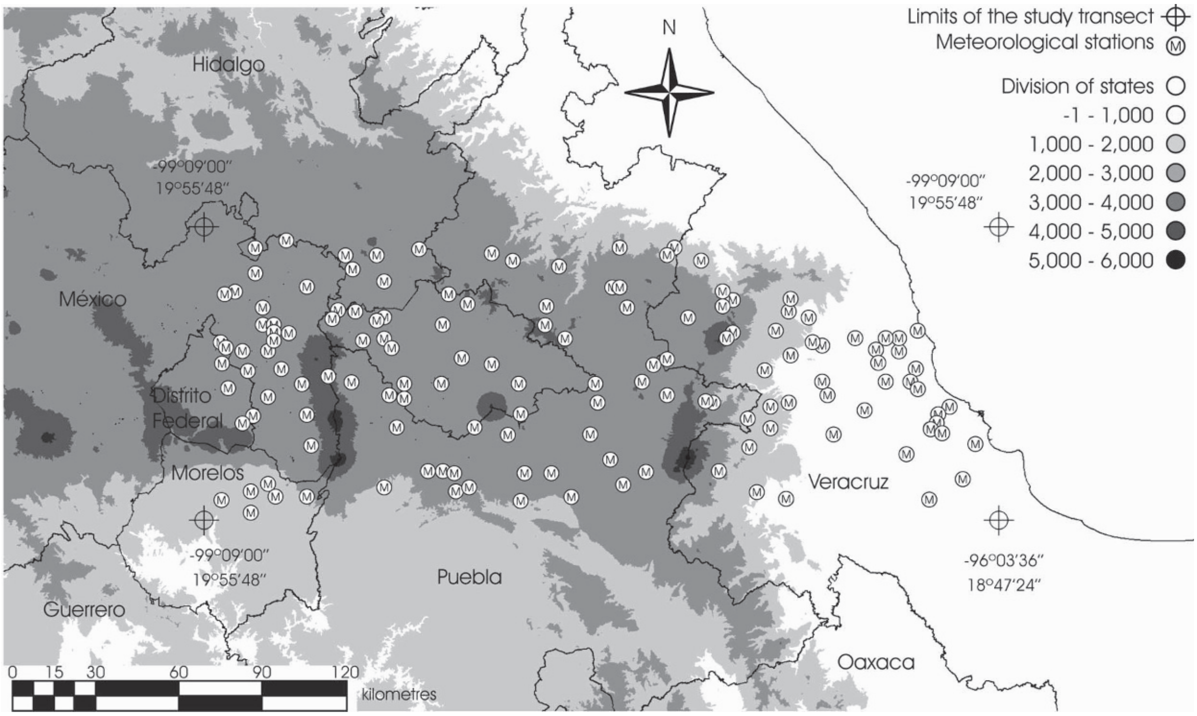
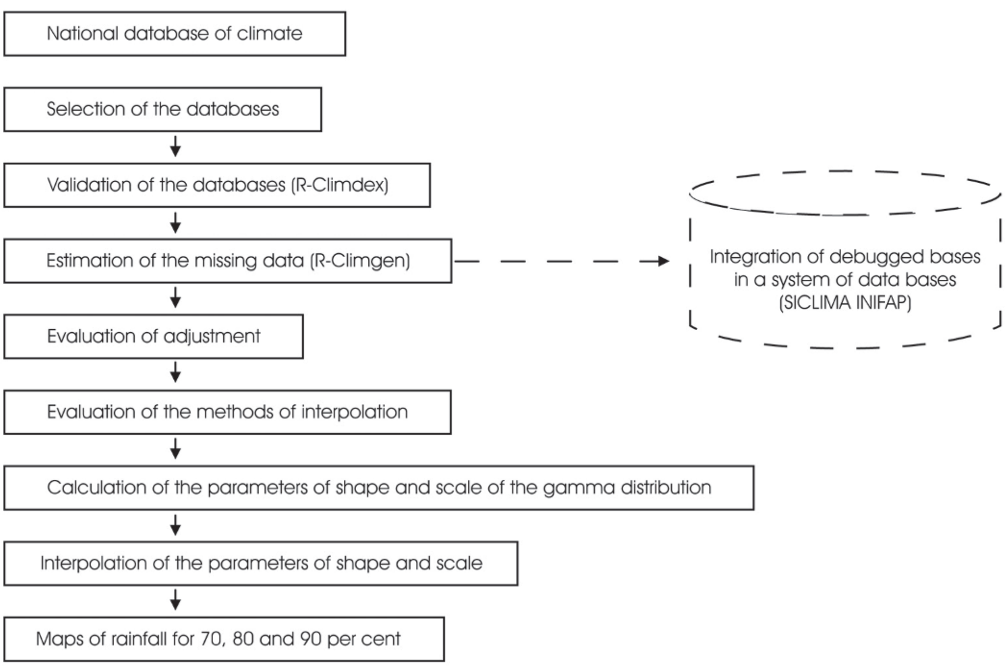


Figure 4.10: Schematic process of methodology of this chapter. **Source:** Authors' research data.



This segment covers an area of 42,323 km², and includes a part of the coastal plains of the Gulf of Mexico and the neo-volcanic axis (figure 4.9). Madera and Jimenez (2005) state that in areas like this one, rainfall is orographic since it originates from an air mass forced to ascend by a mountainous barrier, causing rainfall to be greater in the windward area than in the leeward area.

Figure 4.11: Graphic distribution of the 2,271 weather stations in the Republic of Mexico. **Source:** Authors' research data.

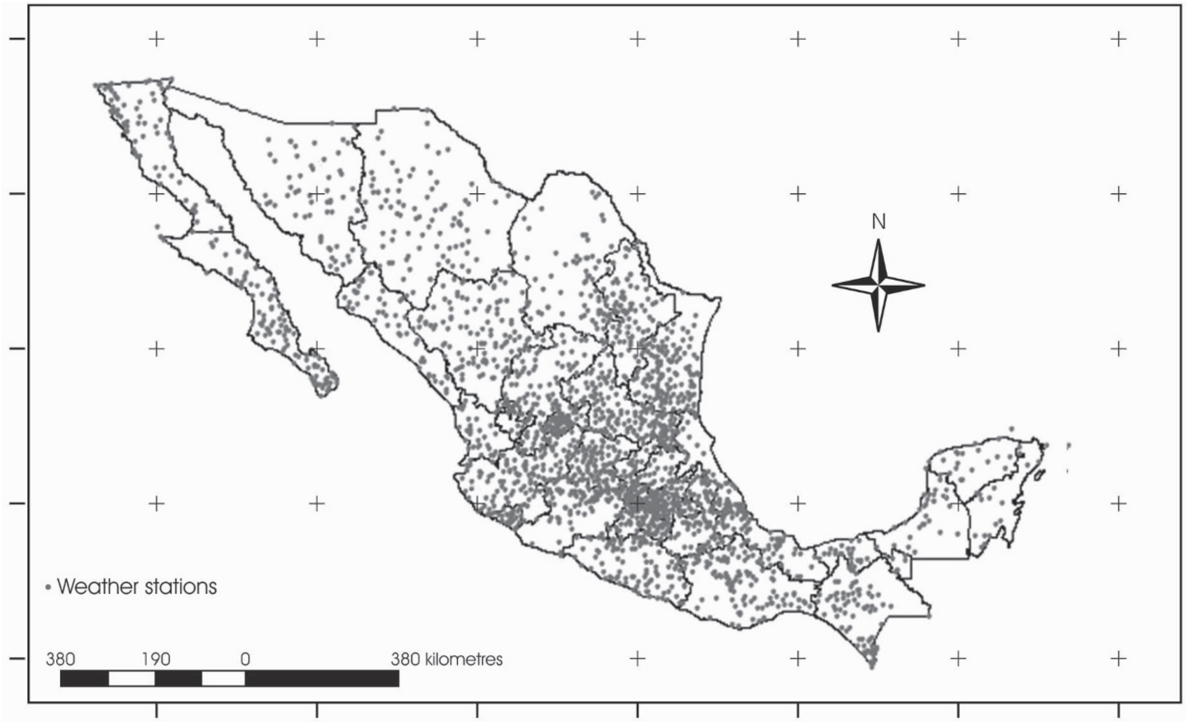


Table 4.2: P values associated with the Wilcoxon and Friedman tests. **Source:** Authors' research data.

Test Comparison Station/Period	Wilcoxon										Friedman				
	Observed *vs* ClimGen					Observed *vs* Lars-WG					Observed *vs* ClimGen vs Lars-WG				
	1	5	10	15	30	1	5	10	15	30	1	5	10	15	30
21040	0.88	0.98	0.06	0.15	0.24	0.72	0.92	0.22	0.99	0.12	0.98	0.97	0.01[b]	0.10	0.16
30128	0.72	0.30	0.07	0.00[a]	0.56	0.21	0.21	0.42	0.00[a]	0.00[a]	0.83	0.47	0.15	0.01[b]	0.00[b]
30004	0.15	0.54	0.14	0.72	0.15	0.15	0.31	0.79	0.49	0.87	0.02[b]	0.88	0.15	0.23	0.49
30008	0.73	0.90	0.94	0.85	0.78	0.47	0.64	0.48	0.16	0.97	0.78	0.76	0.91	0.46	0.90
30066	0.00[a]	0.59	0.96	0.73	0.72	0.00[a]	0.28	0.05[a]	0.76	0.92	0.00[b,c]	0.20	0.04[b]	0.85	0.90
30067	0.02[a]	0.15	0.26	0.34	0.46	0.30	0.02[a]	0.78	0.38	0.06	0.06	0.00[c]	0.18	0.17	0.08
30097	0.57	0.17	0.97	0.18	0.08	0.18	0.82	0.89	0.01[a]	0.15	0.36	0.78	0.52	0.02[b]	0.02[c]
30047	0.87	0.16	0.10	0.04[a]	0.84	0.84	0.19	0.38	0.31	0.95	0.80	0.21	0.59	0.58	0.95
30102	0.73	0.11	0.04[a]	0.41	0.00[a]	0.45	0.24	0.26	0.06	0.52	0.29	0.77	0.20	0.35	0.00[c]
30113	0.32	0.56	0.31	0.00[a]	0.49	0.27	0.75	0.66	0.81	0.70	0.61	0.59	0.63	0.08	0.33
30124	0.92	0.09	0.95	0.70	0.48	0.93	0.72	0.20	0.03[a]	0.15	0.73	0.09	0.54	0.12	0.39
30143	0.25	0.55	0.84	0.24	0.55	0.03[a]	0.96	0.60	0.10	0.76	0.00[b]	0.33	0.96	0.34	0.82

a) Some differences were detected between the observed and generated values, taking a limit rejection value of $\alpha = 0.05$.

b Friedman's multiple comparisons detected differences of the values generated by Lars-WG, taking a limit rejection value of $\alpha = 0.05$.

c Friedman's multiple comparisons detected differences of the values generated by ClimGen, taking a limit rejection value of $\alpha = 0.05$.

With regard to the meteorological information, the database of daily rainfall from 1961 to 2003 was processed for the month of september in 147 weather stations from the National Weather Service, 50 of which can be found in the windward region, and 97 in the leeward region (figure 4.9).

One of the inputs used in this study was the *Digital Elevation Model* (DEM), which represents points

Figure 4.12: Number and percentage of the weather stations in the Republic of Mexico whose rainfall data are and are not adapted to a gamma distribution. **Source:** Authors' research data.

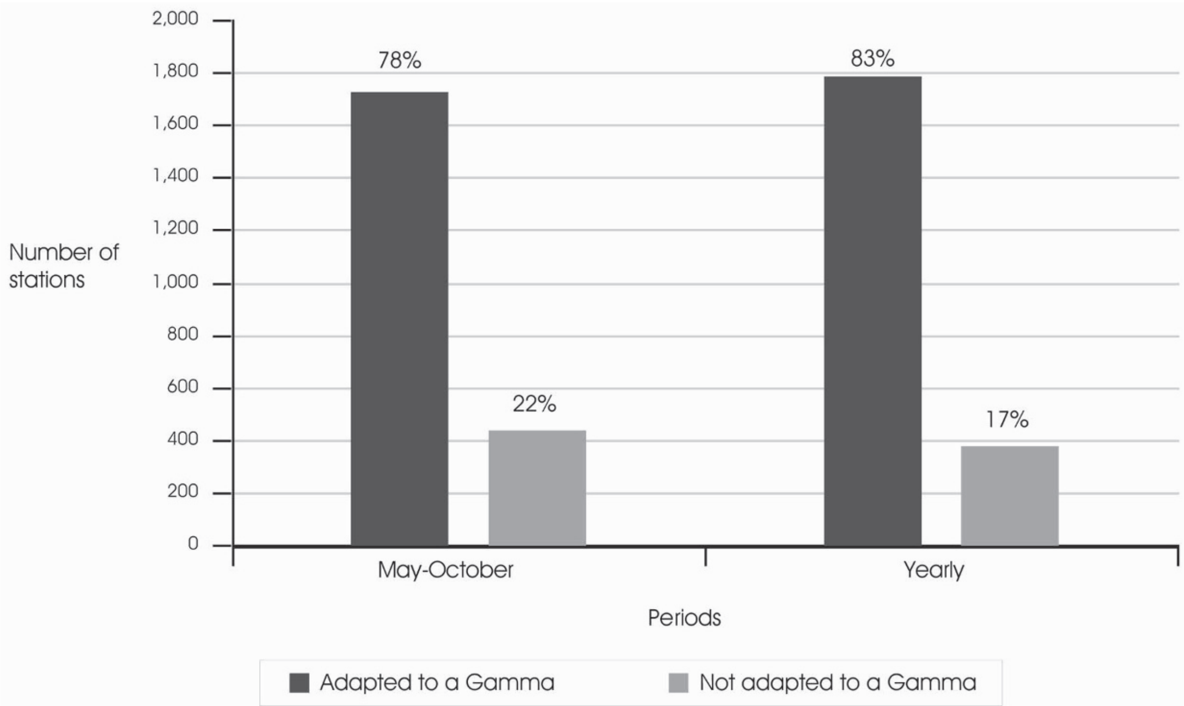


Table 4.3: Summary of non-rejected void hypotheses using Wilcoxon and Friedman's tests. **Source:** Authors' research data.

Concept	**Wilcoxon test**		**Friedman's test**	
	Observed *vs* ClimGen	Observed *vs* Lars-WG	Observed *vs* ClimGen	Observed *vs* Lars-WG
Total performed tests	60	60	60	60
$H_O{}^a$ non-rejected	53	52	56	52
$H_O{}^a$ rejected	7	8	4	8
Percentage of $H_O{}^a$ non-rejected	88%	87%	93%	87%

a) H_O: There are no differences between the observed values of rainfall and those generated by ClimGen and Lars-WG.

over a surface of the territory whose geographical location is defined by the coordinates X and Y; and to which we added the Z value corresponding to elevation (INEGI, 2006). The DEM used in this work has a 90 meter resolution. For this study, we drew on this segment of the area of interest to be used as an auxiliary or secondary variable in the generation of surfaces through a interpolation process of data from geographic points by the Co-Kriging Method and Thin Plate Smoothing Spline.

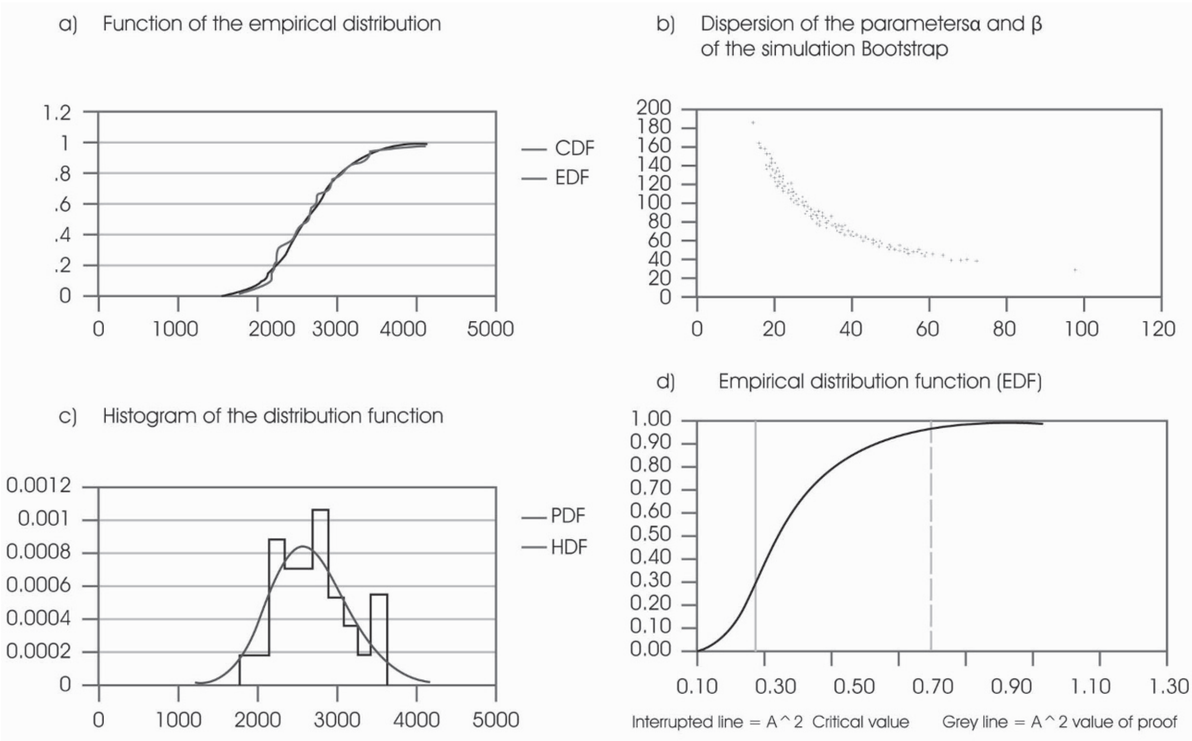
To perform this process, we used a *Geographic Information System* (GIS) that may be defined as an organized integration of hardware, software, geographic and personal data, designed to register, store, analyse, manipulate and thoroughly display information that has been graphically referred to; some of them may include modules to perform the interpolation of data points. The GIS used were the extension of the geostatistical analysis of ArcGis 8 (ESRI, 2002) and the 4.3 version of the Anusplin software developed by Hutchinson (2004). Figure 4.10 shows the methodology that was used for developing this work.

4.6 Results

Once the above selection criteria were applied, only 2,271 climate stations were selected (figure 4.11). As mentioned before, the missing values were calculated with the ClimGen program and the resulting values P of the non-parametric tests are shown in table 4.2.

Based on these outcomes, we determined the percentage of the null hypotheses non-rejected (table 4.3).

Figure 4.13: Result from the application of the Cheng algorithm for the 'El Palote' weather station. **Source:** Authors' research data.



Based on this, the use of these generators may provide us with reliable climatic data, since the ones obtained by both have 'high' levels of coincidence in comparison with real data. Both ClimGen and Lars-WG have a well defined format of data entry for generating missing records; and this involves prior processing of the source of information. Notwithstanding this, we considered it feasible to work with ClimGen because its estimations are close enough to those originally recorded, and because it is easy to use in comparison with the procedure that must be followed with Lars-WG, which requires a higher number of previous processes to set an adequate data format.

On the density function in the gamma distribution, the information about rainfall from 1,727 weather stations fitted to the gamma distribution for the period May-October, and from the 1,786 weather stations for the yearly period (figure 4.12).

Figure 4.13 shows some results from the application in the operation of algorithms already described for the 'El Palote' station.

The first graph (a) shows the function of the cumulative and empirical distribution. In this case, we can visually observe whether the station data adapt to a gamma distribution. Graph (b) shows the histogram of the data presented in the chart of empirical distribution, which lets us see where the data are over- or underrated. Graph (c) displays the results from the iterations in the parameters α and β through which it is possible to define the confidence interval of such parameters. Finally, in graph (d) we can see the collocation of the critical value from the Anderson-Darling test, and the calculated value by the application of this test.

Tables 4.4 and 4.5 show a summary of the parameters and resulting statistics. Thus, it is important to emphasize that only a few of the stations are shown, those whose rainfall data adapt to the gamma distribution, while others did not adapt to this distribution.

After generalizing the outcomes (table 4.5), we can now see the average value of the parameters; the national average for all years was 31, which is higher than the one used by García (1965), and considered acceptable when carrying out this study. The national average annual rainfall calculated for the 2,165 stations corresponds to 846 mm; the national average for for α parameter is 19.68 and 55.40 for the β parameter.

According to the law of the maximum likelihood estimator would correspond with a normal distribution. The value of the Anderson-Darling test was 0.38, an acceptable value when contrasted with the national critical value of the Anderson-Darling test of 0.74.

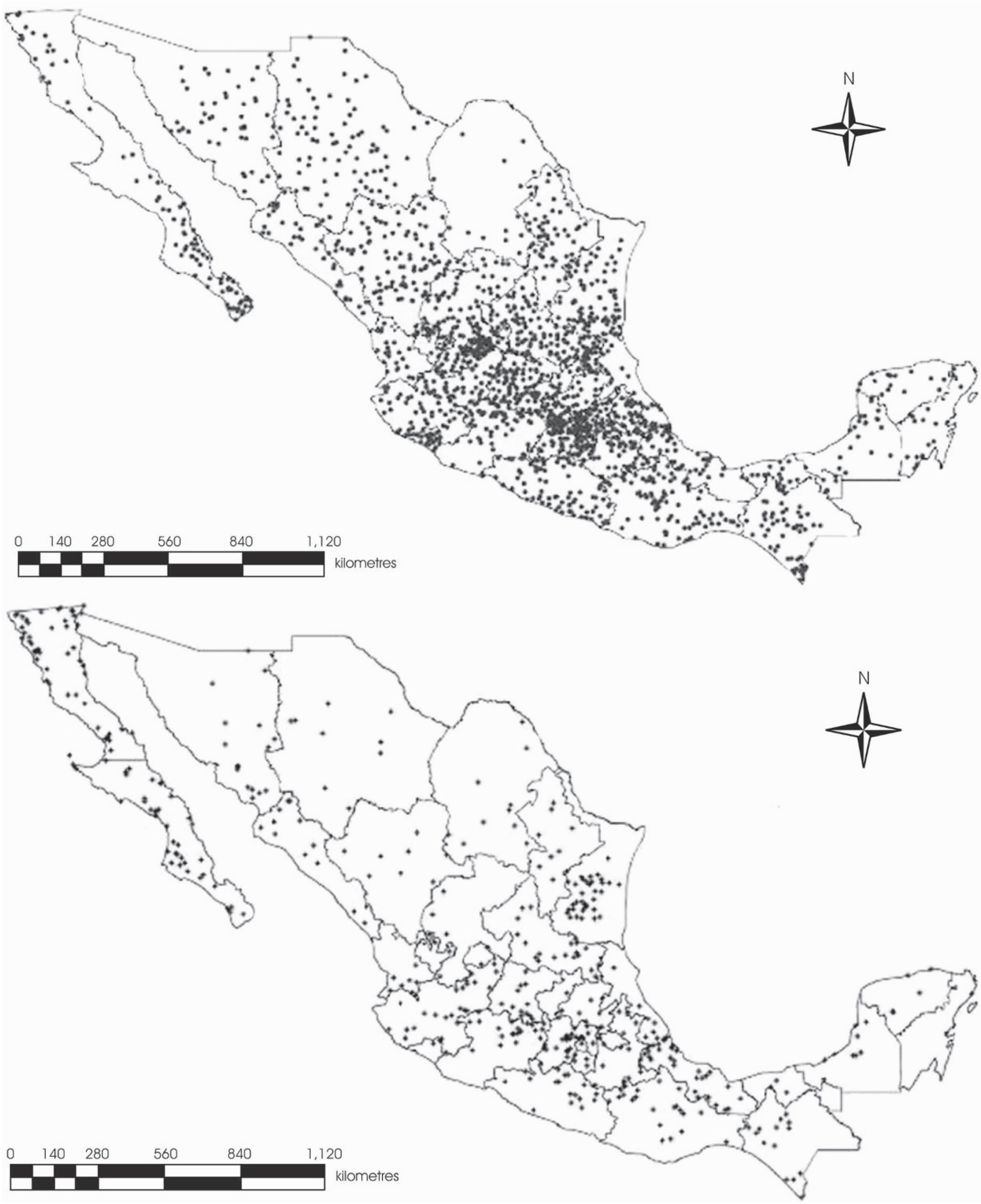
Table 4.4: Outcome parameters for the May to October period for 10 stations. **Source:** Authors' research data.

Period of May-October									
Station	**Years**	**Lowest Pp**	**Highest Pp**	**Average Pp**	**Shape**	**Scale**	**AD**	**Critical value AD**	**P-value**
Fitting to the Gamma Distribution									
Zaragoza	38	93	537	264	6.42	41.16	0.14	0.75	0.98
Catemaco	33	1,024	2,495	1,695	23.95	70.75	0.15	0.78	0.98
Cam. Agr. Exp. de Río Gde.	34	700	1,975	1,329	15.54	85.50	0.15	0.75	0.98
Presa El Rejón	35	104	815	382	5.91	64.68	0.14	0.74	0.99
Temascalcingo	37	423	1,095	715	20.08	35.61	0.12	0.77	1.00
Non-fitting to the Gamma Distribution									
La Chona	23	0	818	499	10.77	48.36	1.29	0.77	0.00
Los Herreras	28	201	2,555	612	2.44	250.33	0.97	0.75	0.01
Belén	38	0	141	41	1.10	37.98	0.95	0.80	0.02
El Marquez	21	109	395	282	8.87	31.82	0.81	0.75	0.04
Las Gaviotas	38	910	2,280	1,494	28.40	52.60	0.73	0.71	0.05
National average of stations adapted to the gamma distribution	31			741.97	17.58	56.30	0.38	0.74	0.48

Table 4.5: Outcome parameters for the yearly period for 10 stations. **Source:** Research data.

Yearly Period									
Station	**Years**	**Lowest Pp**	**Highest Pp**	**Average Pp**	**Shape**	**Scale**	**AD**	**Critical value AD**	**P-valor**
Fitting to the Gamma Distribution									
El Varejonal	41	535	1,493	894	20.26	44.14	0.17	0.75	0.95
Irapuato	41	367	1,079	671	15.99	41.94	0.17	0.73	0.96
El Palote	43	216	1,072	588	8.40	69.97	0.17	0.77	0.96
Yurecuaro	35	486	1,152	763	22.61	33.74	0.15	0.75	0.97
Bustamante	34	279	864	513	13.98	36.65	0.14	0.76	0.98
Non-fitting to the Gamma Distribution									
S.Miguel del Monte	23	183	1,949	1,018	4.44	229.03	1.00	0.74	0.01
Chicontepec Tejada	40	1,216	4,163	1,947	11.30	172.37	0.93	0.74	0.02
Chapulhuac	33	274	1,258	897	14.27	62.88	0.87	0.72	0.02
Las Flores	42	581	1,308	973	36.10	26.96	0.77	0.70	0.03
La Herradura	19	215	534	366	12.83	28.57	0.73	0.71	0.05
National average of stations adapted to the gamma distribution	31			846	19.68	55.4	0.37	0.74	0.49

Figure 4.14: (a) Geographical distribution of stations whose rainfall data adapt to a gamma distribution with a parameter of shape (α) and a parameter with scale (β); (b) Geographical distribution of stations whose rainfall data did not adapt to a gamma distribution for the national territory. **Source:** Authors' research data.



This value, generated by bootstrap (1000 iterations per station) is very similar to the value reported as critical for other distributions (Lognormal, Normal and Weibull).

All this could be taken as a general national criterion by using the Anderson-Darling test to assess the match with a sample of historical series of rainfall. Also, within this, there are values that correspond with the p-value that was, at a national level, 0.50, a value that is extremely distant from the rejection range for the alternative hypothesis, and so, at the national level, we need not reject the hypothesis that the country's rainfall series adapt to a gamma distribution in practice at any established level of significance. Similar outcomes can be found for the May-October period, and they are shown in table 4.4.

From this, several important outcomes may arise; for instance, if we compare the average rainfall reported in table 4.5 with that from the May-October period, we can assume that, based on the analysed sample, 87 per cent of the rainfall reported yearly takes place in the May-October period. Regarding the gamma distribution parameters, we can assume that there are no significant changes for the α and β parameters for annual rainfall and for that occurring in the May-October period. The Anderson-Darling values, the Anderson-Darling critical values, and the p-value associated with the test are practically the same.

Figure 4.14 shows the spatial distribution of stations whose values of rainfall adapt to a gamma distribution (a); and in (b) are shown those that do not demonstrate such behaviour. It is important to point out that these distributions did not adapt to the behaviour of the gamma distribution principally because there are some suspiciously wrong data, and these are very sensitive to the test. Therefore, it might be useful as a detection tool for data that do not fit subsequent studies.

An important aspect to highlight is that the gamma distribution adapted itself adequately to stations in very different geographic location, ranging from regions of heavy rainfall, such as the humid tropics, to areas with scarce rainfall, i.e. arid and semi-arid zones.

When it was confirmed that the rainfall data for each station fitted to the gamma distribution, by using a routine developed by Cheng (2006) in the Basic Visual Compilator, a database was created for the α and β parameters based on the rainfall data from the May-October period with their geographical coordinates. Later on this same process was performed for the yearly period. The resulting database was quite useful for carrying out an interpolation process for the α and β parameters through an Anusplin program developed by Hutchinson (2004); Sanchez and Diaz (2008) considered it ideal for such a process because it uses the geomorphology of the territory to calculate the interpolated values.

To obtain the images shown in figure 4.15, the information for the May-October period provided by 1,727 weather stations was used, whereas for figure 4.8 the information supplied by 1,786 weather stations for yearly rainfall was used.

Starting out from the distributions of the α parameter shown in figures 4.15 and 4.16, we can observe that for the peninsular regions of Baja California, the northern mountain ranges and plains, as well as for parts of the coastal plains of the Gulf of Mexico, the precipitation tends towards lower values of rainfall, whereas for the regions of the Sierra Madre Occidental, the neo-volcanic axis, the Gulf plains, and the rest of the country´s south-east, the rain tends to be much more symmetrical, thus recording higher levels of rainfall.

4.6.1 Interpolation of Rainfall Data at a 70, 80 and 90 Per Cent Probability

Conde et al. (2004) claimed that Mexican agriculture is principally developed during the spring-summer cycle (S-S), since, according to data from the Department of Agriculture, Livestock, and Rural Development (SAGAR, 1998), the S-S cycle covers 80 per cent of the working surface of the country.

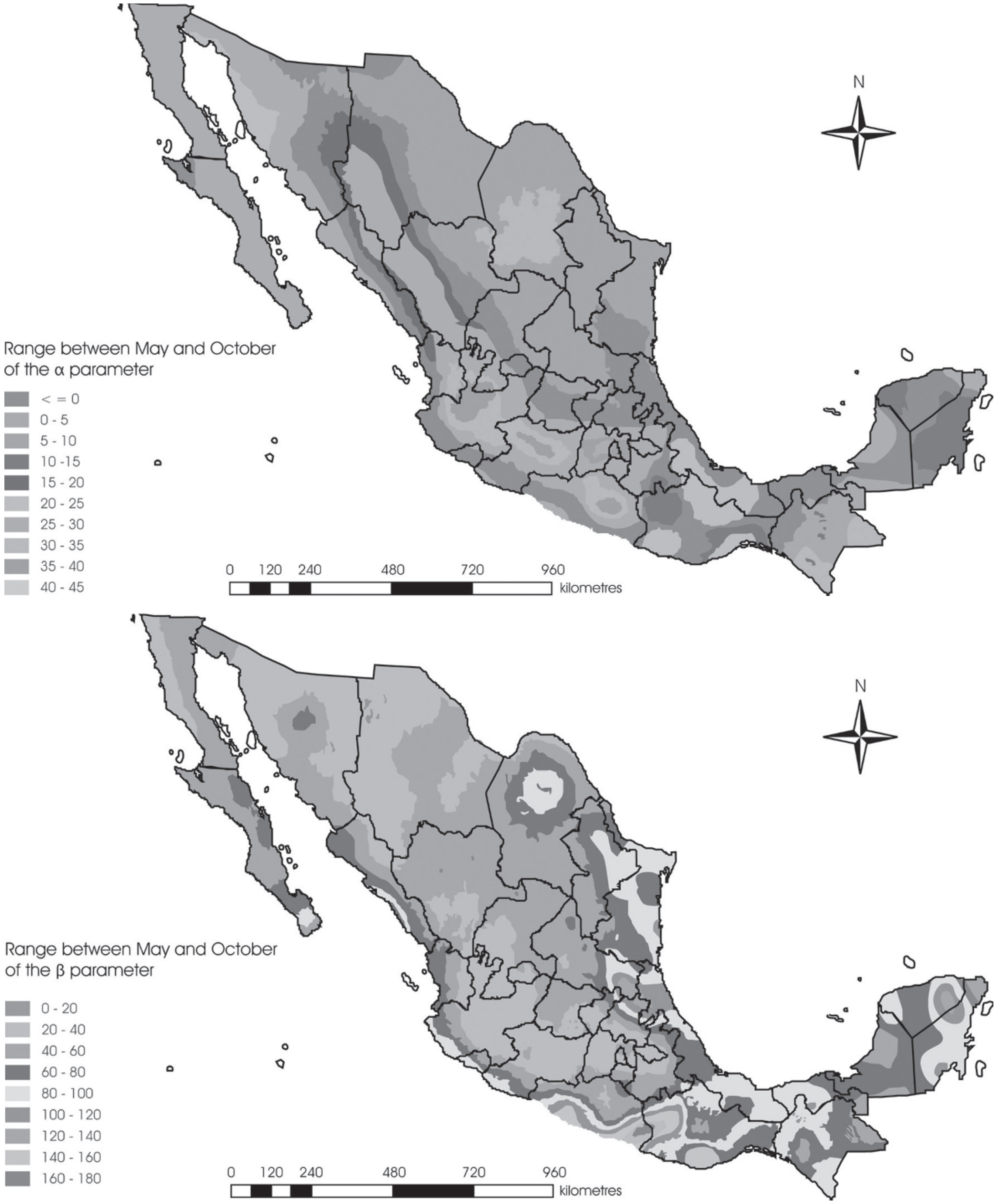
Based on the α and β parameters for the gamma distribution, we calculated the rainfall levels for the May-October and yearly periods for each station, thus forming a database with a respective geographical location and rainfall levels at 70, 80 and 90 percentages, then interpolated these values through Anusplin to produce continuous surfaces of rainfall to those percentages already mentioned, and that are shown in figure 4.15 for the May-October period and in figure 4.16 for the yearly period.

4.7 Conclusions

4.7.1 Integrating Quality Climatic Data Series

Due to the simplicity of tabular presentations and charts of atypical data, it was suggested we use the R-ClimDex software as an alternative method of evaluating the quality and volume of data from the historical daily series of rainfall. ClimGen turned out to be a reliable climatic generator for the estimation of missing daily rainfall data, since it relies on existing data and only generates the missing information. It was

Figure 4.15: Range demarcation of the α and β parameters for gamma probability distribution in the national territory corresponding to the accumulated rainfall for the May-October period based on the calculated information from 1,727 weather stations. **Source:** Authors' research data.

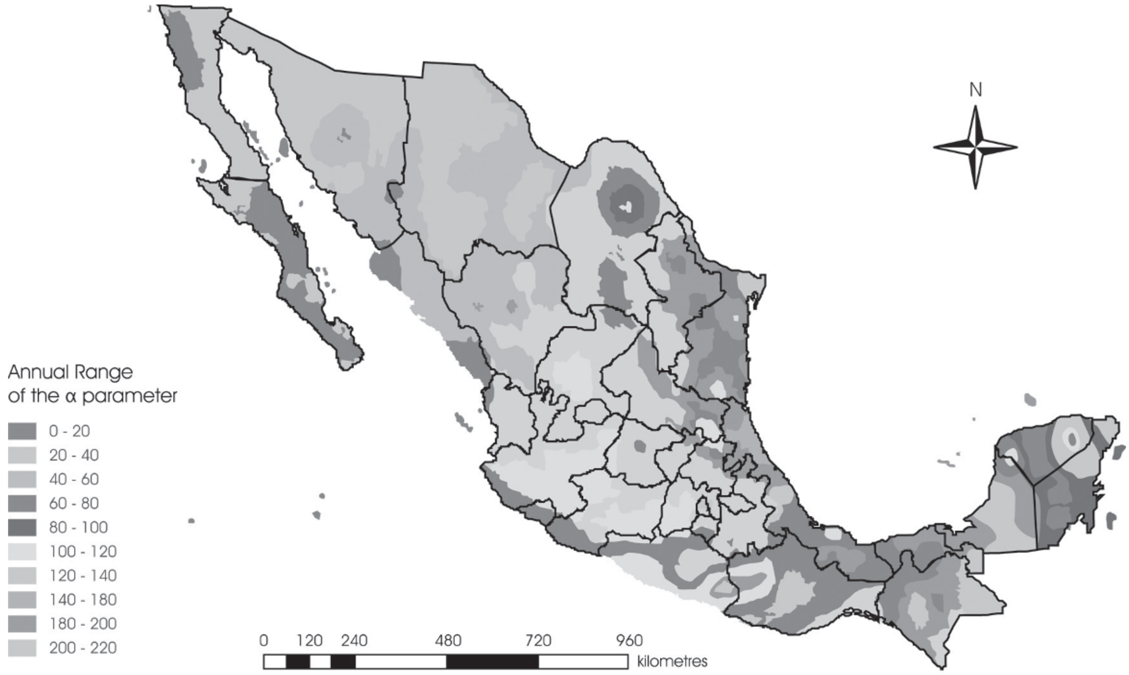


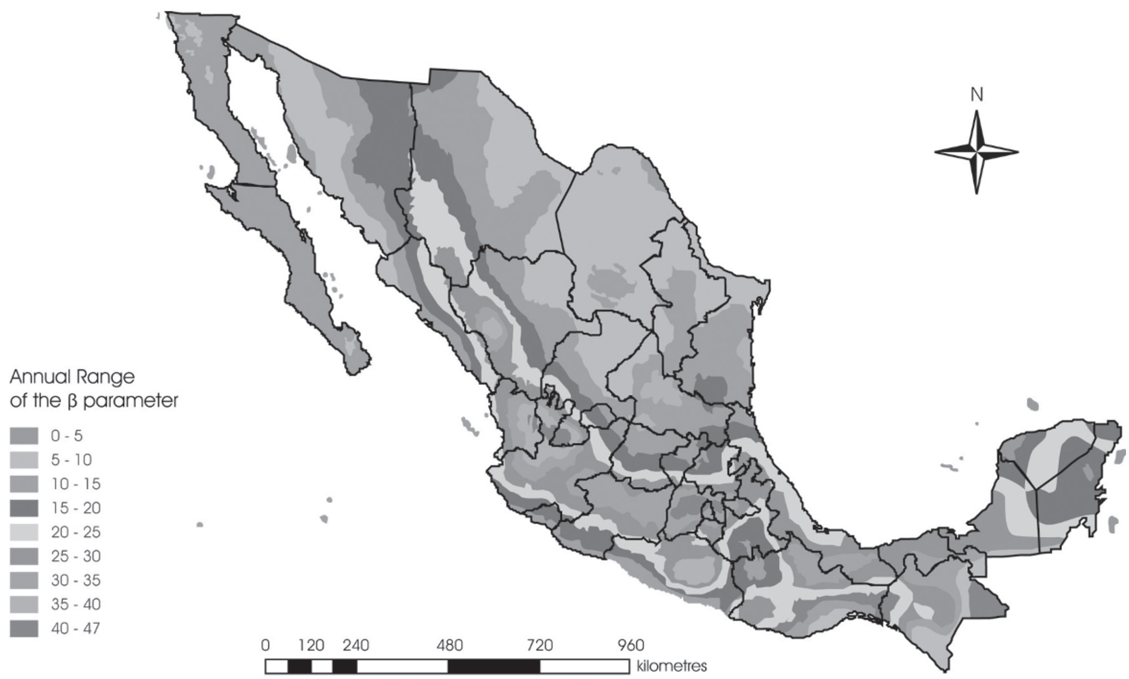
also the most precise when it was compared, through statistical tests, with other climatic generators.

4.7.2 Fitting Rainfall to the Gamma Distribution

The distribution of the theoretical gamma probability for the parameters is adequate for probabilistic mod-

Figure 4.16: Range demarcation of the α and β parameters for gamma probability distribution in the national territory corresponding to the accumulated rainfall of the yearly period based on the calculated information from 1, 786 weather stations. **Source:** Authors' research data.





elling of rainfall in Mexico, as well as for the yearly records, and for those of the May-October period; and we suggest using it in the calculation of climatic anomalies, and the prediction of extreme events. There was no geographic, climatic or spatial pattern that might influence the fitting with this distribution, this can be used for any kind of weather or geographic space in Mexico.

4.7.3 Adequate Spatial Interpolation Method of Rainfall

The suggested method for spatial interpolation of rainfall is the *Thin Plate Smoothing Spline* (TPSS), since it registered the lowest value of error in the interpolated prediction map when compared with a few other interpolation methods (Kriging, Inverse Distance Weighted – IDW, and/or Co-Kriging). Therefore, the authors recommend using the interpolated maps for the shape and scale parameters of the gamma distribution to model the hydrological cycle, climate change, and also for the probabilistic calculation of extreme events in Mexico.

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5 Coastal Aquifers of Sonora: Hydrogeological Analysis Maintaining a Sustainable Equilibrium

Miguel Rangel Medina, Rogelio Monreal Saavedra and Christopher Watts

5.1 Introduction[1]

A coastal aquifer is a hydrogeological unit whose basic characteristic is that one of its geographic limits is the sea or the coastline. In this sense, the unit is generally understood as representing the water discharge from a continental hydrologic basin. This type of aquifer is highly sensitive to groundwater extraction by wells, since unlike a continental aquifer where over-exploitation is compensated by taking water from storage, coastal aquifers allow the entrance of sea water instead. This is due to a hydraulic imbalance that results from the fact that extraction exceeds recharge with a consequent loss of hydraulic head. Under these conditions a cone of depression is formed that will persist as long as excessive groundwater extraction continues. Therefore, in a coastal aquifer, if pumping exceeds recharge, a loss of hydraulic head occurs and the marine water will penetrate.

Along the coast of Sonora, low meteoric precipitation combined with the over-extraction of groundwater has produced a saline intrusion which has gradually penetrated aquifers of the coast of Hermosillo and Guaymas-Empalme for up to 40 km inland, producing a zone of saline contamination. Other aquifers to the north and south show a front of marine intrusion and a zone of mixing which must be monitored systematically. The advance of this contamination has been accelerated during the last 30 years by population growth and water demand.

Lack of study and analysis becomes crucial and complicates water management and impedes development and basin sustainability. Only by hydrogeological actions will it be possible to stop and perhaps reverse aquifer damage that today seems irreversible. Therefore, it is very important to define this strip of brackish water with certainty, since it now constitutes an aquifer whose water could be extracted for various uses after desalination treatment.

It is necessary to define the parameters of the marine intrusion and thickness. Given the robust economic development of this region, extraction of this brackish water will allow tourism or industrial developers to pump water without producing a greater marine water entrance, and we will keep a dynamic balance of saline and fresh water. This brackish water will help retract marine penetration, thus generating greater environmental hydrological impact in the North-west of Mexico.

During the last 10 years, the Department of Geology of the University of Sonora has carried out a series of research and technical studies in collaboration with different Mexican government offices of water administration and regulation. Among the works are those which strengthen basic knowledge of the regional hydrology of north-western Mexico, and the characterization of the basins and aquifers within the area, along with their hydrogeological and administrative boundaries as determined by the *National Water Commission* (CONAGUA). The present work is a summary of these studies in two aquifers in the north-west: Costa de Hermosillo and Puerto Peñasco.

These studies have had physical, chemical and biological components that have laid the foundations of water knowledge since 1999. The scope of these studies has been equally varied, ranging from those starting with no prior knowledge, to those that give continuity to climatological, hydrometric and hydrodynamic observations (piezometric) already systematically being performed by CONAGUA in different basins of the hydrologic region, and where the interpretation of regimes and historical developments creates added value. However, the highlight of these tasks has been observing the hydrological cycle, which is fundamental to knowledge of a basin and especially of its discharge zone, which in these cases are the coastal aquifers. Observing and recording are the two

1 Key words: Coastal aquifer, Sonora aquifer, marine intrusion.

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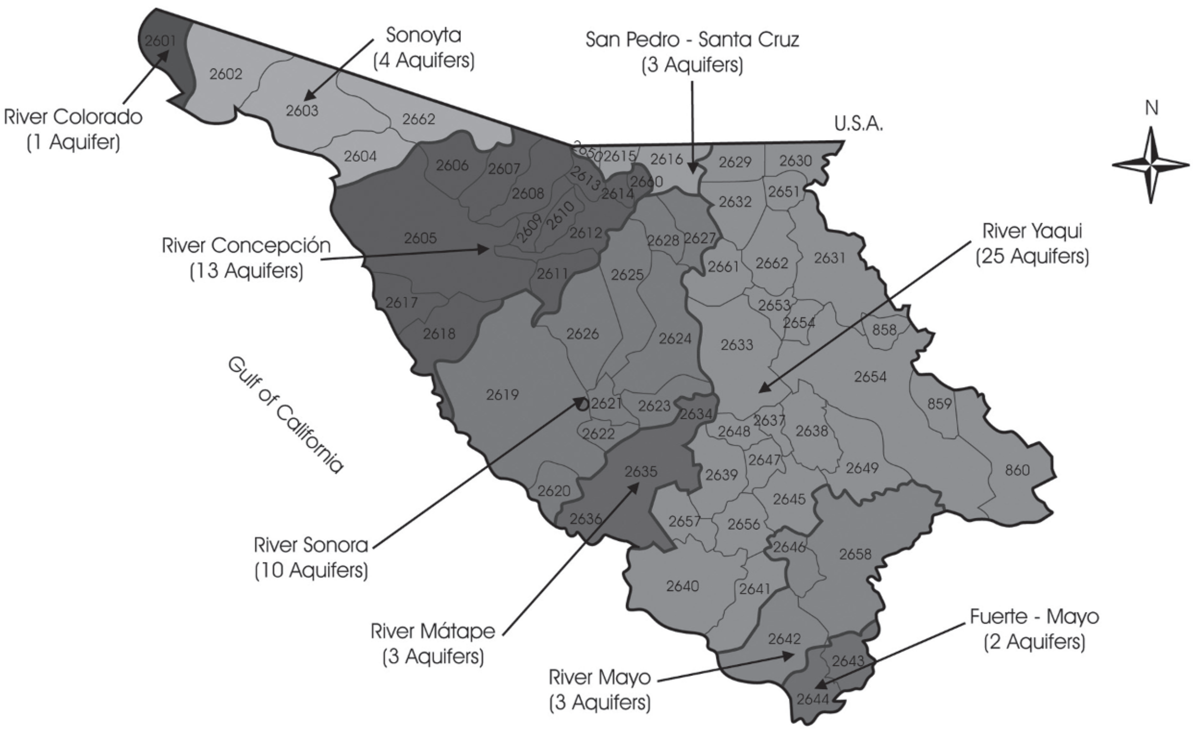
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_5,

Figure 5.1: Location of administrative basins and aquifers in the North-west region of Mexico. **Source:** CONAGUA (2007).



actions required when it comes to understanding historical events, because without data there is no retrospective for addressing the past, and therefore there is no sustenance for the future when the planning of resource management is required.

In the North-west region, low water availability makes the need for databases more critical. Because of its characteristics as a desert and semi-desert region, the North-west of the country has infrequent and localized rainfall. According to Bull's rainfall regime classification (1991), the Sonoran coastal areas are arid (table 5.1).

Table 5.1: Classification of climate types by average annual precipitation. **Source:** Bull (1991).

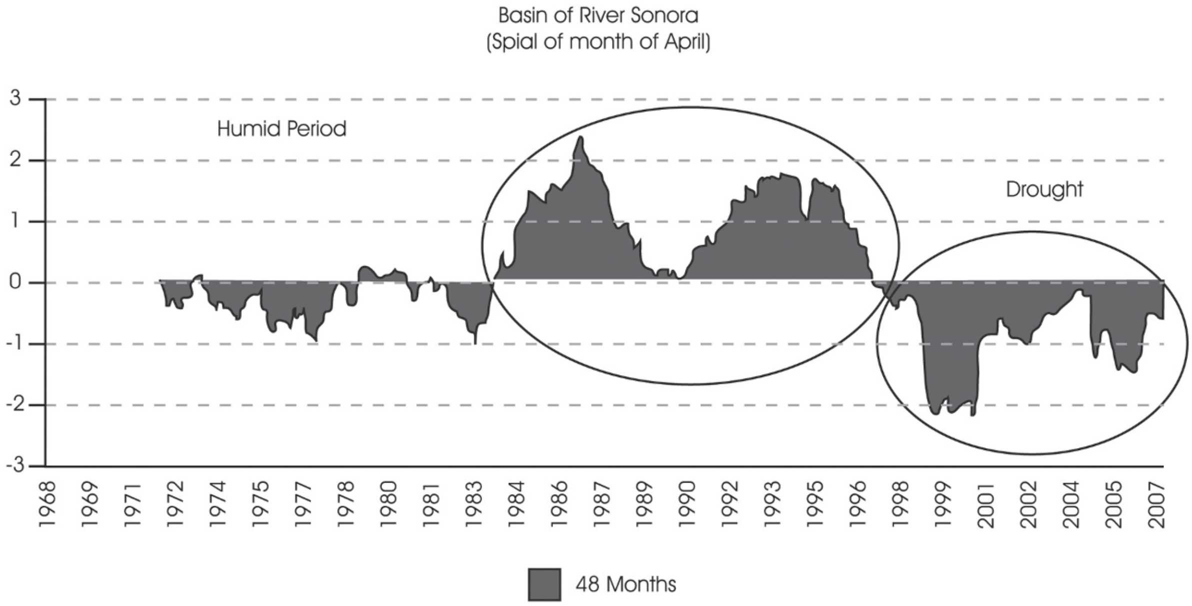
Classification	Annual average precipitation (mm)
Extremely arid	< 50
Arid	50 – 250
Semi-arid	250 – 500
Subhumid	500 – 1000
Humid	1000 – 2000
Extremely humid	> 2000

These rains produce quasi-perennial surface run-off in the Yaqui and Mayo river basins in the south of Sonora that constitute 40 per cent of the territory and generate 89 per cent of the run-off in the region, with 5,459 hm^3 per $year^{-1}$. The rest of the region survives with low recharge rates from infiltration. The mean recharge is 2707.08 hm^3 $year^{-1}$ and the extractions are around 2784.91 hm^3 $year^{-1}$, according to volumes authorized by CONAGUA, which gives a regional deficit of -77.83 hm^3 $year^{-1}$ (Rangel Medina, 2006).

The North-west administrative region of the country has a total area of 205,291 km^2. It is practically equal to the surface of the state of Sonora, although 12.5 per cent is part of the state of Chihuahua (figure 5.1).

This region consists of seven basins that show a high sensitivity to changes and abrupt alterations, producing alternating cycles of drought and floods, given the alteration of various hydrometeorological phenomena that generate extreme rainfall periods. It is possible to observe an example of such variation by calculating the annual average for the 1960–1995 cycle, which gives 354 mm of rainfall, while for the period 1996–2006 it averages 316 mm, much lower than the previous period, indicating a period of drought in the state (figure 5.2).

Figure 5.2: Drought indexes in the Sonora River Basin. **Source:** CONAGUA (2007).



Considering the low rates of precipitation mentioned above, the dynamic balance of the water is extremely fragile, so that intensive extraction by pumping can easily exceed the small amount of short-term recharge of the hydrological cycle that includes seasonal or multi-annual fluctuations. The management of this regime can be made more flexible by including water storage in aquifers to supplement surface water in times of scarcity. However, if the regional flow system is not understood it could be risky to play with aquifer storage when recharge zones are so far away and travel time is so long. Hence the value of piezometric measurements in the basins under study as the main source of water supply of the region lies underground. Therefore, it is important to realize that the importance of piezometric observations is both technical and socio-economic.

The first one is based on the need to generate a comprehensive understanding of a watershed where the effects of meteorological and hydrological drought (as a transitory phenomenon) have been affecting, in the case of the Sonora River, the supply of water to the city of Hermosillo. In this capital city the primary source was the Abelardo Rodríguez dam, fed by the Sonora River, but since October 1998 the run-off has been almost null to null, and so since that year the supply has gradually been reaching 100 per cent from groundwater.

The importance of this basin is due to the fact that one of the coastal aquifers beneath it, the Costa de Hermosillo aquifer, is globally most affected by marine water intrusion. It is also worth remembering that according to the historical records analyzed by Montgomery (1998), the hydrometeorological drought phenomenon occurs with a frequency of once every 10 years, and may have a duration ranging one to three years. This being so, during the past 50 years three critical periods of extremely severe drought have been registered in this region (figure 5.2). The socio-economic aspect is mainly based on the fact that the largest population of the state is settled along the Sonora basin with almost 800,000 inhabitants, who generate the highest percentage of the gross domestic product of the State, and the coastal aquifer has been taken as the best current and future support option.

5.2 Objectives

The main objective of this work is to demonstrate the evolution and state of marine water intrusion in the North-west of Mexico. Specific goals in all studies that have been made of coastal aquifers were to define the position and geometry of the brackish water wedge (front of saline interface), to obtain the geometry of the aquifer, to get to know the hydrostratigraphy, to characterize the geochemistry of the water, and to define the physical properties of the aquifer and groundwater in a three-dimensional model.

5.3 Working Method

In the determination of the sources and the mechanism of marine water intrusion, a variety of hydraulic, geophysical and geochemical techniques were used. The information obtained allowed us to characterize the hydraulics of the aquifer, the hydrostratigraphy, and the characteristics of marine water intrusion migration. The studies performed included organic and inorganic geochemistry analyses and ground hydrology supported by *geographic information systems* (GIS). This information can be used to develop strategies that incorporate the availability of natural and artificial recharge to control the descent of the potentiometric level and degradation of water quality.

Methodologically, the study of these aquifers began with the revision of previous work, enabling us to examine and obtain data or parameters that might be useful for the interpretation of the characteristics and evolution of the system; hence it is evaluated from the initial conditions of the aquifer. In the field, the status was defined with a census of groundwater wells, selected by their best conditions, and those where pumping tests were performed to obtain the hydraulic parameters of the aquifer, as well as the physical characteristics of the saturated environment, the lithology, and the definition of the rock units that act as the limits of the aquifer. Also, a gravimetric technique was used to define the geometry of the basement, and the different hydrogeological units were obtained with the use of transient electromagnetic soundings (TEMs) that correlated with the lithology of existing wells and showed the aquifer hydrostratigraphy, the geometry of the areas of interest, and its hydraulic capacity.

The physical and chemical characteristics of water were identified, its hydrogeochemical relationships were interpreted, and the origin and relative age of the water was supported by isotopic techniques (Rangel Medina, 2003a; Szynkiewicz et al., 2008). Finally, the quality of water was obtained for practical purposes for users, and plotted in profiles and graphics, which included continental, coastal and marine water.

A criterion considered representative for the interpretation of water quality based on measurements of electrical conductivity (EC) is set by the *American Public Health Association* (APHA, 1995), which rank the quality of water in accordance with the following criteria:

a.) 100 to 2000 $\mu S\ cm^{-1}$ at 18°C (freshwater);
b.) 2000 to 5000 $\mu S\ cm^{-1}$ at 18°C (brackish);
c.) 5000 to 45000 $\mu S\ cm^{-1}$ at 18°C (sea water);
d.) 45000 to 1000000 $\mu S\ cm^{-1}$ at 18°C (brines).

5.4 Conceptualization and Study Basis of Coastal Aquifers

Understanding a system of modern flow conceptualized in terms of water that has infiltrated less than 50 years ago, and evaluating its availability, requires a large amount of information and human and material resources; it also requires multidisciplinary tools that can provide conceptual hydrogeological and operational models. It is essential for water administrators to differentiate the recent infiltration of water from the older millenary systems. Only in this way is it possible to sort and regulate an aquifer and to control or sustain its extraction, while maintaining its hydrodynamic balance. Therefore, it is necessary to identify the likely origin, age and movement of groundwater recharge to an aquifer with the transit of regional flow, because the management of the resource must differentiate the characterization of those aquifers that feed from local recharge with multi-annual recovery.

Regional flow systems in Sonora coincide with Tóth's (1963) theory, which states that the recharge area falls in the drainage divide watershed, and the discharge area in the bottoms of valleys; then in terms of this, the systems often have recharge periods of thousands of years whose origins might even go back to interglacial Holocene time. This process is aggravated by population growth and the consequent intensive pumping of groundwater, as is the case with the aquifer of Costa de Hermosillo, located in the zone of discharge of the Sonora River basin (figure 5.3).

5.5 Hydrogeological Deterioration of Coastal Aquifers of the Northwest of Mexico

Coastal aquifers are located at the outlet of watersheds, where fresh water is discharged into the sea. When these aquifers are over-exploited, phreatic levels are reduced and, when they are lower than mean sea level, the flow regime is reversed, so that sea water intrudes into the aquifer (Van Dam, 1999) and levels of salinity increase, leading to water wells being abandoned. Therefore, saline water intrusion is an invasion of marine waters or water from marine deposits due to the lowering of groundwater levels, so that the intrusion threatens the water supply in areas near the coast. Once the causes of marine water intrusion are determined, it is necessary to exercise strict control to reverse the changes in spatial distribution, to control

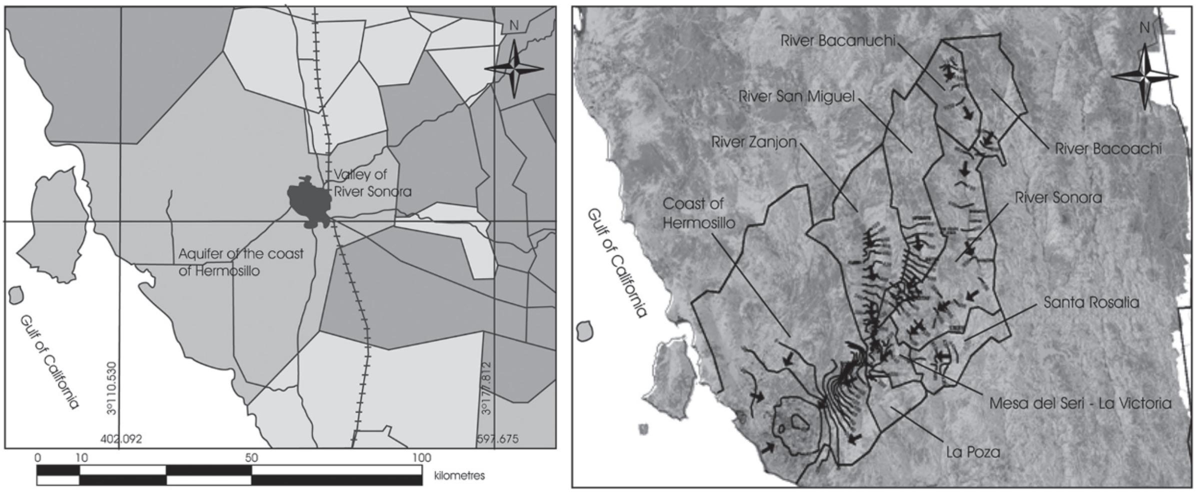


Figure 5.3: Left: The location of aquifer zones in the Sonora River Basin; shading represents different districts of rural development (DDR). Aquifers in the valley whose recharge is modern and the Coast of Hermosillo (CH) with millennial recharge are shown. Right: the administrative division of the aquifers showing DDR 141 (CH) with direction of regional flows. **Source:** Rangel Medina (2006).

the amount of groundwater being extracted by pumping, and possibly to apply artificial recharge techniques (Rangel Medina et al., 2005).

In Mexico, experience with detrital coastal aquifers is limited; studies by various authors focus geographically on North-west Mexico, mostly on the state of Sonora and very specifically on the aquifers of Puerto Peñasco, Caborca, Costa de Hermosillo, Sahuaral, Guaymas-Empalme, Yaqui and Mayo valleys, and further south on Guasave in the state of Sinaloa. Different experiences have been reported in the state of Yucatán, but take place in a karstic medium, so research methods and study disciplines are different (González, 2005; Casares, 2005; Graniel, 2005). Traditionally, it is accepted as a general rule that karstic aquifers have many peculiarities that affect the characteristics of the flow and that this sets them apart from the detrital aquifers (Morell, 2003).

Marine water intrusion is induced and aquifer conditions deteriorate because of the lack of administrative control of the aquifer, the lack of management, and the irresponsibility of the users. These conditions have been apparent since the 1950s and today inertia in water use has allowed four of the most important aquifers of the region to be 1.57 times and 1.94 times over-exploited (Casares, 2004). That is, the available water (recharge) is 62.6 km^3, the authorized extraction is 98.2 km^3, and the real extraction 121.7 km^3 (Casares, 2004). This situation is reflected in constantly declining water levels which undermine water storage in the coastal aquifers of Caborca, Costa de Hermosillo and Guaymas-Empalme, the last two with extensive penetration of marine water. In this situation, no new groundwater developments are allowed in almost 80 per cent of the state of Sonora, with the exception of the upper portions of the Yaqui and Mayo rivers, where CONAGUA (2004a) considers that 6 per cent of the groundwater is renewed annually. Of all the work reported on saline intrusion in coastal aquifers, the Costa de Hermosillo is perhaps not only the oldest that has been analysed, but the one in which most research has been undertaken in Mexico (CONAGUA, 2002, 2005). Frequently, however, such hydrogeological problems are not, or cannot be, adequately quantified, due to shortage of data (Van Dam, 1999).

5.6 How Can Intrusion be Avoided?

A scheme for the exploitation of any kind of coastal aquifer is shown in figure 5.4. The basic principle comes from the hydrometeorologic balance, where 'effective precipitation' generates a potential volume of recharge. Demands are assigned to different users, since the ecological demands assigned to living beings and wetlands are considered an important part of the demand, as well as sufficient water to avoid saline intrusion. The fundamental difference between coastal and continental aquifers is that in the latter, storage change defines the volume with which demand or consumption can be operated (figure 5.4). In the water balance for coastal aquifers, the output should always be greater than zero; otherwise, there will be

Figure 5.4: Left: the universal balance model in a basin showing the demands of users. Right: the balance of water for conditions of continental aquifers. **Source:** Rangel Medina (2006b).

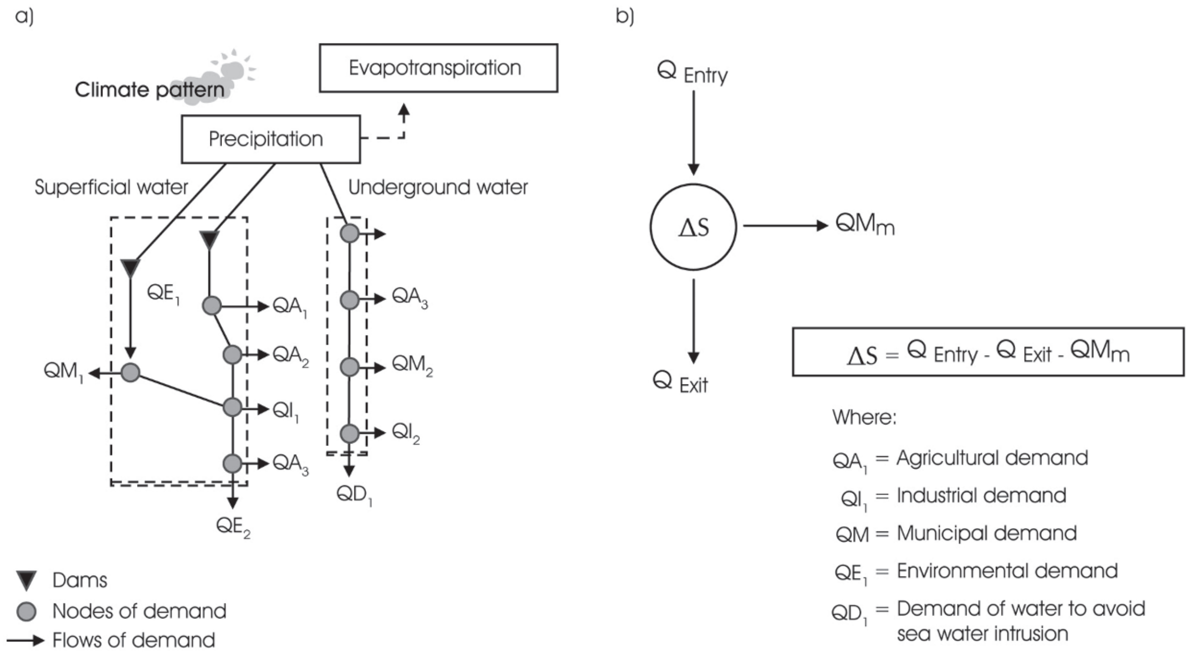
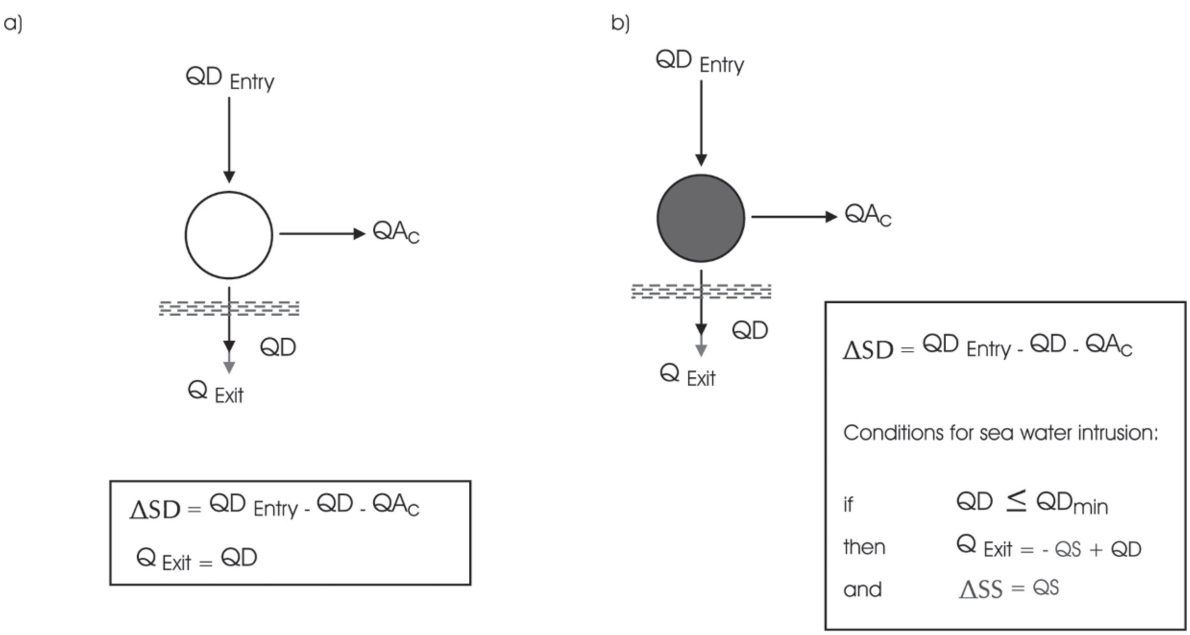


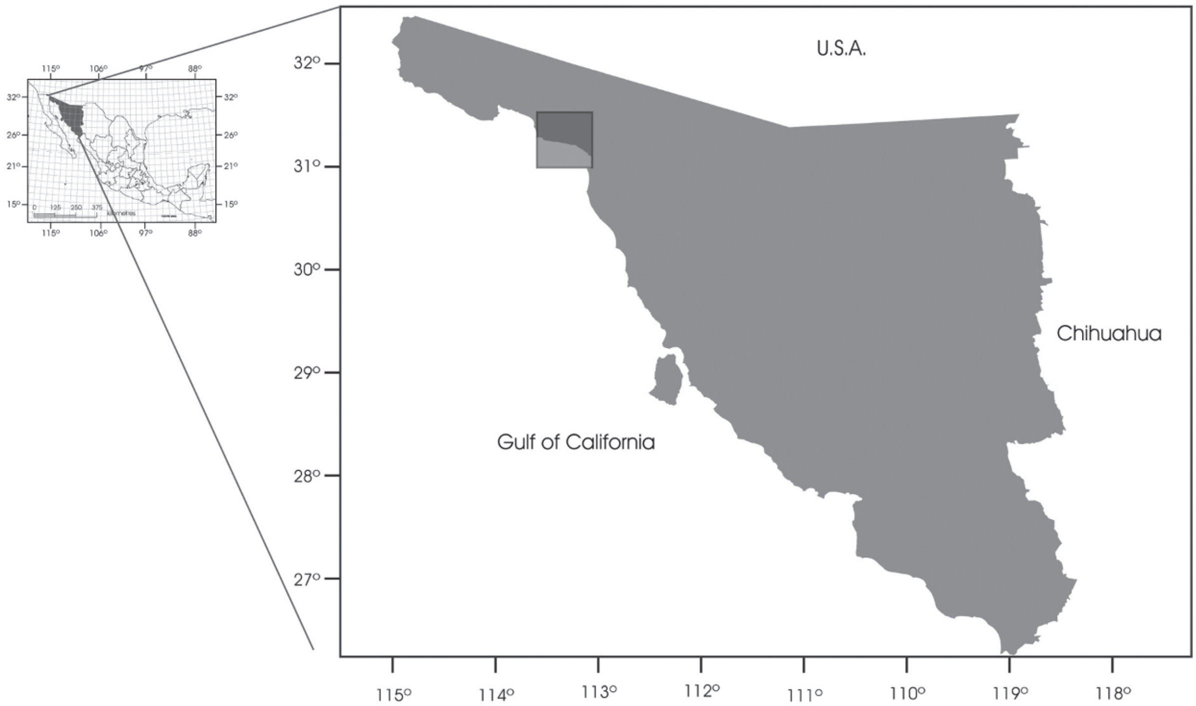
Figure 5.5: Left: conditions of water balance in coastal aquifer. Right: negative water balance and penetration of the marine water intrusion. **Source:** Rangel Medina (2006b).



penetration of marine water into the aquifer (Rangel Medina, 2006b). When imbalance is generated, the conditions for marine water intrusion will be induced, and when the flow of demand is greater than the input flow, there is no exit, and then the output flow disappears and the mass balance in this change is covered by sea water (figure 5.5).

When marine water intrusion is already present, it is important to know how to operate a mined aquifer, which is still subject to intensive use, in a stabilized form, and to define the chances of recovery and

Figure 5.6: Location of the Puerto Peñasco aquifer**. Source:** Designed by the authors.



pumping control. To do this, it will be necessary to continue and to intensify the observations of the hydrodynamics and geochemistry of groundwater.

5.7 Case Studies of Intruded Coastal Aquifers in the North-west of Mexico

In this section, case studies of coastal aquifers with marine water intrusion are presented. The aquifers selected are Puerto Peñasco and Costa de Hermosillo, not only because of the large number of studies and data that are available, but also because of their economic importance and the current conditions of extensive marine water intrusion.

5.7.1 Puerto Peñasco Aquifer

This aquifer is located in the extreme north-west portion of the state of Sonora in the great Altar desert in hydrologic region No. 8, and corresponds to one of the most arid regions of Mexico (figure 5.6).

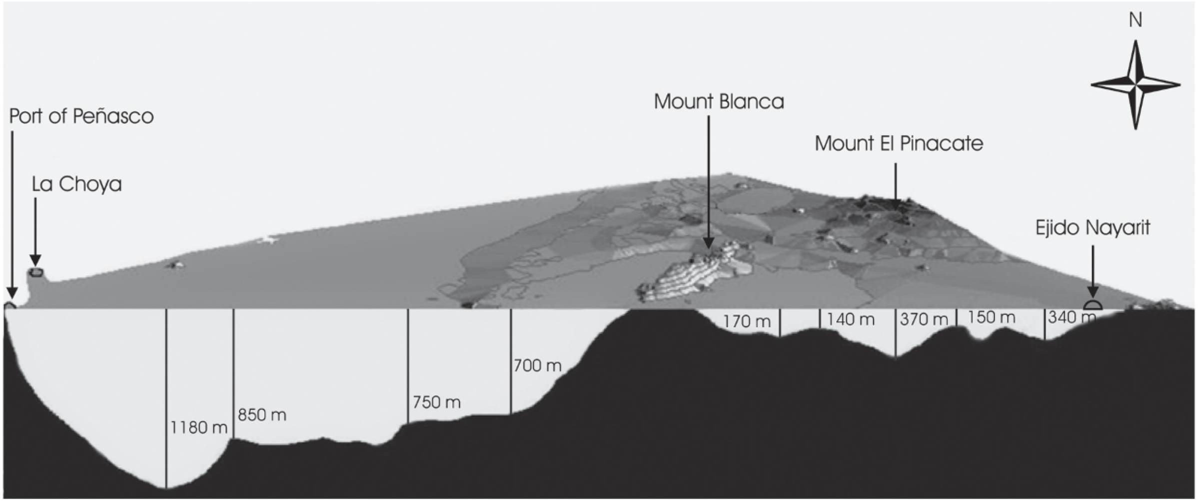
Rainfall is scarce, with mean annual precipitation of 109 mm, so that water resources are very limited and unable to provide for increasing demand, given that the region has experienced explosive growth in the development of tourism during the past ten years. The infrastructure for surface water storage in the region is almost zero due to reduced rainfall, which makes the development of the region dependent on groundwater extracted from the Puerto Peñasco aquifer. This aquifer is barely able to support the needs of drinking water for the population, and does not have sufficient capacity to increase the supply to meet the demands in the current growth of tourist activities. Given these hydrogeological conditions, CONAGUA studied the possibility of extracting brackish water from the saline interface area in the aquifer, in order to desalinize this water and to support development by providing a secure supply of water for the tourist resorts (Rangel Medina, 2006; CONAGUA, 2007a).

The physiography of the region consists mostly of alluvial plains with dunes, dune fields, saline coastal plain with marshes, and south of the El Pinacate discontinuity, steep volcanic ranges (Sierra El Pinacate) and basaltic high plains with craters. These physiographic elements are those that provide beauty in the landscape and are an important tourist attraction of the region.

5.7.1.1 Results

The morphology of the littoral zone was determined to be a product of the distensive tectonic province of the “Basin and Range” (De Zcerna, 1988) and of the opening of the Gulf of California. As a result there are

Figure 5.7: Gravimetric profile of the Puerto Peñasco aquifer (the alluvial fill is shown in light colour, crystalline basement in dark). **Source:** designed by the authors.



a number of sedimentary tectonic *grabens* formed by fallen blocks, whose regional crystalline basement is constituted by granitic intrusives that form part of the Larámide Batholith of Sonora containing numerous 'roof pendants' of ancient rocks covered in discordance by post-batholithic rocks and recent deposits (Rangel Medina, 2003). From the hydrogeological point of view these *grabens* contain sedimentary deposits with highly permeable channels that facilitate the process of marine water intrusion towards the continent (Flores et al., 1998; Monreal et al., 2000). Based on gravimetric data (Exploraciones del Subsuelo S. A., 1971), a map of the crystalline basement depth was obtained that shows the development of an alternation of tectonic *grabens* and horsts significantly oriented NW-SE, reaching depths greater than 1500 metres (figure 5.7).

The results show that the salinity of the coastal zone, in terms of electric conductivity, registers values of >6000 µS cm^{-1}. The continental zone shows conductivities ranging between 1377 and 2170 µS cm^{-1} and so is between fresh and brackish. This water comes from the wells that provide the drinking water to the town of Puerto Peñasco, located inland, between 30 and 45 km from the population.

Along the coastal strip there is a brackish water fringe, differentiated from north to south by its width, thickness and salinity. Profiles with brackish water intrusion wedge are shown (figure 5.8). The best aquifer unit identified for purposes of exploitation, in terms of water quality, lies to the north with a thickness of less than 10 m that limits the capacity for development. To the south this unit is between 50 m and 100 m thick, and down to 200 m deep. Water quality can vary between 6,500 and 50,000 µS cm^{-1}. The average width is 10 km from the coastline. From this limit to the area of wells for water supply to Puerto Peñasco, there is a protection strip of approximately 45 km. Also, the brackish water strip is located in a different tectonic *graben* from that containing the freshwater aquifer, so this acts as a buffer between the two kinds of water (figure 5.7).

The wedge of marine water intrusion is a mixture of modern marine water and the small amount of groundwater that flows towards the sea. The unit that contains this wedge shows materials with thin to thick granular texture. Below the wedge of brackish water, geophysical profiles together with the water samples obtained in wells show that there is another unit with sandy to fine texture material containing water brines with very high conductivity, up to 90,000 µS cm^{-1}.

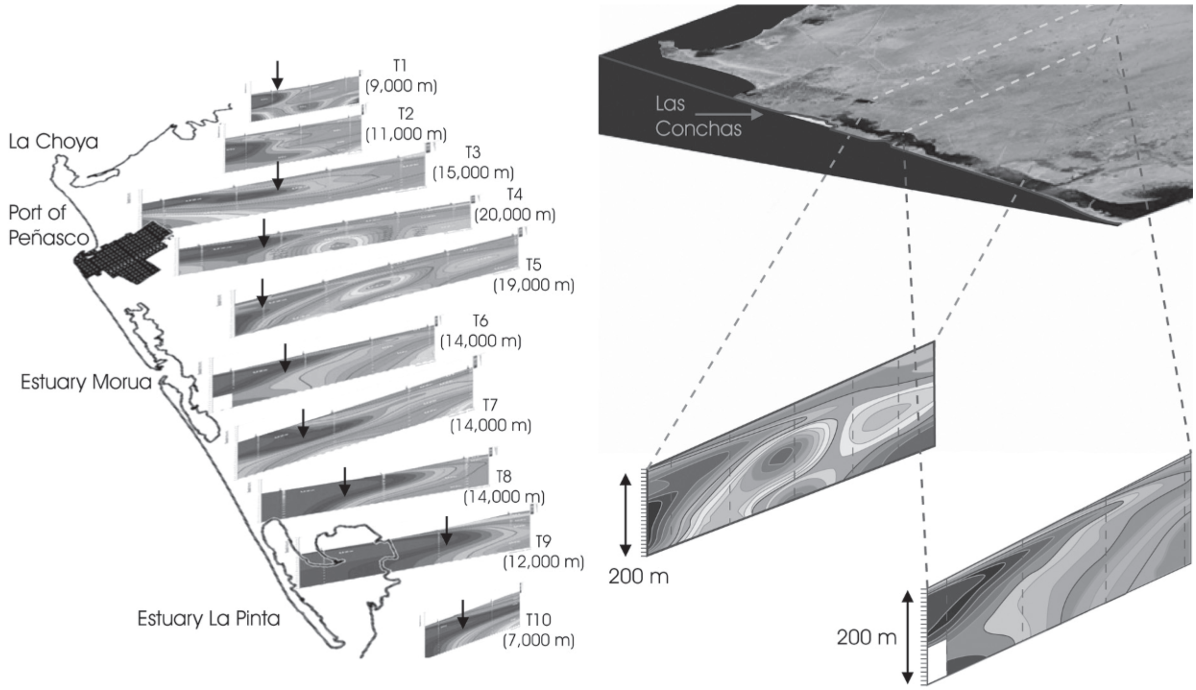
The centre zone is defined from Puerto Peñasco towards the east; this zone has less volume available since penetration is limited by the rocky border of the city of Puerto Peñasco, which has served as a barrier to the marine water intrusion.

5.7.2 Costa de Hermosillo Aquifer

The Costa de Hermosillo aquifer is located in hydrologic region number 9 in central Sonora. It comprises an area of 1738.76 km^2. The development of the Costa de Hermosillo aquifer has made an important contribution to economic and social development in the region (figure 5.9).

That is why it is extremely worrying that excessive pumping has created serious problems for both water

Figure 5.8: Marine water intrusion profiles showing thickness and extension along the coast of Puerto Peñasco. **Source:** Rangel Medina (2006a).



supply and quality, as considered by Tulipano (2003) who states that: "This means that the extraction of groundwater in an aquifer is greater than a certain limit, which if exceeded, a number of consequences are observed. These are lowering of the phreatic level and, in the case of coastal aquifers, water quality degradation by marine water intrusion."

5.7.2.1 Results

The morphology of the littoral zone is a product of the distensive tectonic province of the "Basin and Range" (De Zcerna, 1988) and the opening of the Gulf of California. As a result there are a number of sedimentary tectonic *grabens* formed by fallen blocks, whose regional crystalline basement is constituted by granitic intrusives that form part of the Larámide Batholith of Sonora that contains numerous 'roof pendants' of ancient rocks covered in discordance by post-batholithic rocks and recent deposits (SARH, 1977, 1982; Rangel Medina, 2003b). From a hydrogeological viewpoint, these *grabens* represent high permeability channels that facilitate the process of marine intrusion towards the continent (Flores et al., 1998; Monreal et al., 2000).

During the first 20 years of operation (1947–1967), salinity steadily increased in the aquifer by the loss of hydraulic load, due to the large cone of depression caused by excessive pumping of groundwater that reached its maximum of 1,200 hm^3 in 1965. Since then, the progressive depletion in levels has reduced static levels to as much as 65 m below sea-level. This process has reversed the hydraulic gradient at the coastline, with sea water providing artificial 'recharge' to the aquifer (figure 5.10), currently estimated to be 98 hm^3 per year, penetrating various areas (figure 5.7). It is estimated that the decrease in the volume of water stored in the aquifer is around 37,500 hm^3 and amounts to ~60 per cent of its original storage.

The advancing intrusion of saline water into the aquifer has forced many users of agricultural wells to abandon them in the last three decades, as pollution reached the wells making the water unsuitable for irrigation. A campaign to determine the *vertical electrical conductivity* (VEC) log was carried out in thirty wells. A successful interpretation of the behaviour of the VEC at 40, 70 and 100 m depth was performed, showing the migration of saline intrusion. The area covered (both lateral and vertical) was enough to interpret the advance of the salinity, which was correlated with a network of 408 TEM soundings that were strategically distributed in order to define the hydrostratigraphy and the geometry of the marine water intrusion front (figure 5.11).

Figure 5.9: Left: satellite image interpretation of the Costa de Hermosillo. Right: topography of the crystalline basement in the Costa de Hermosillo. **Source:** Modified from Monreal et al. (2000).

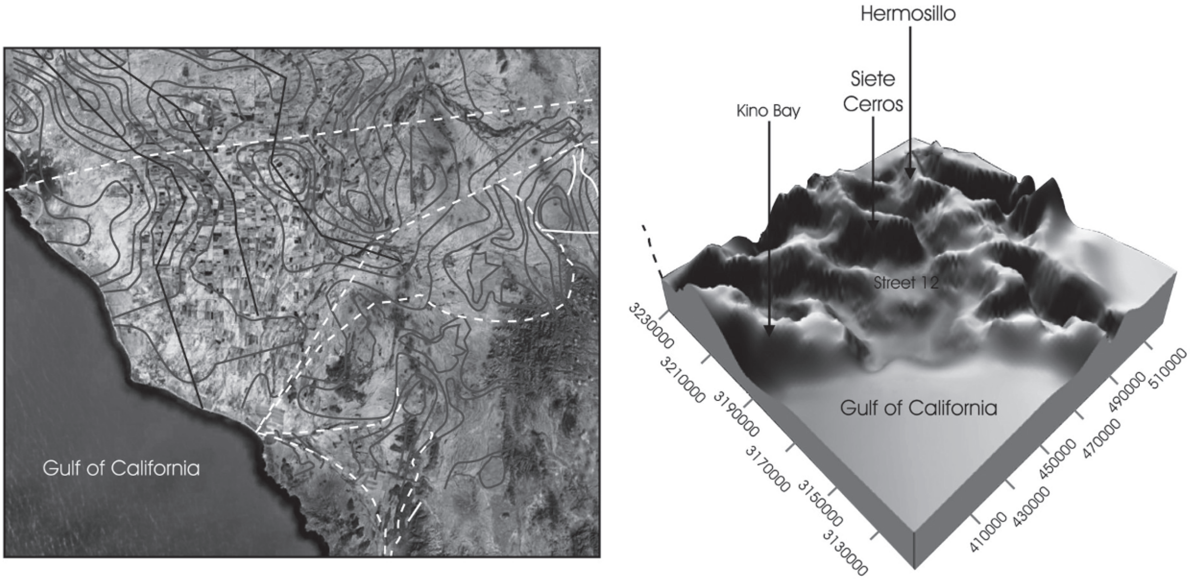
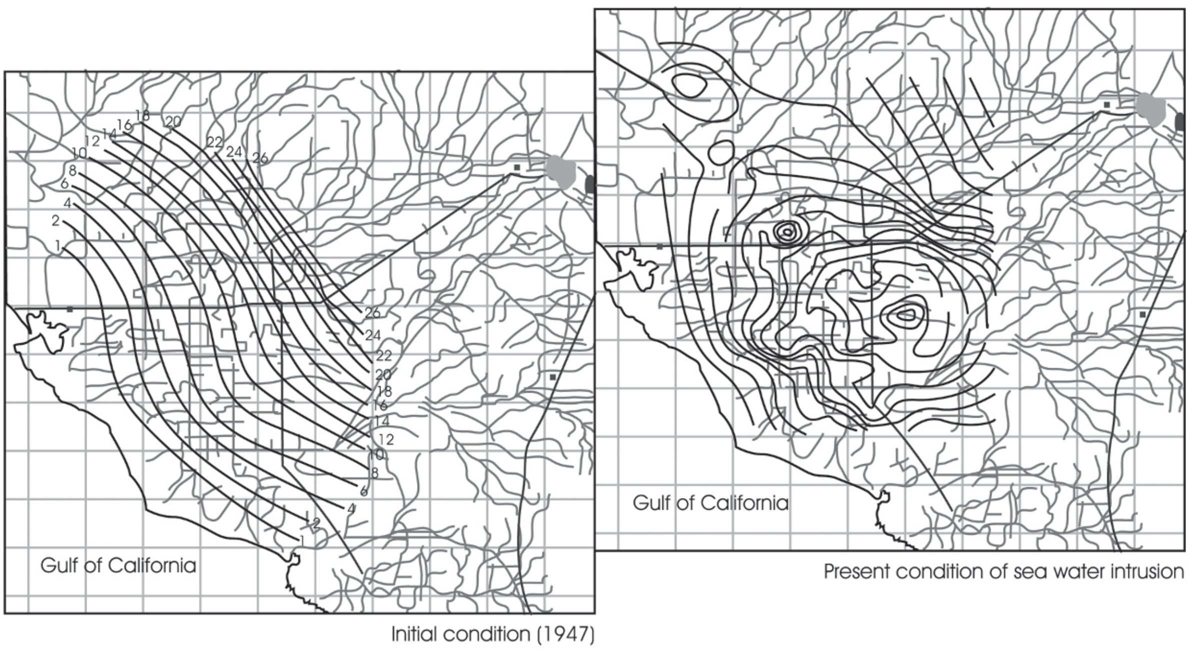


Figure 5.10: Piezometry in the Costa de Hermosillo aquifer. Left: for the year 1947. Right: for the year 2006. **Source:** Rangel Medina (2006b).

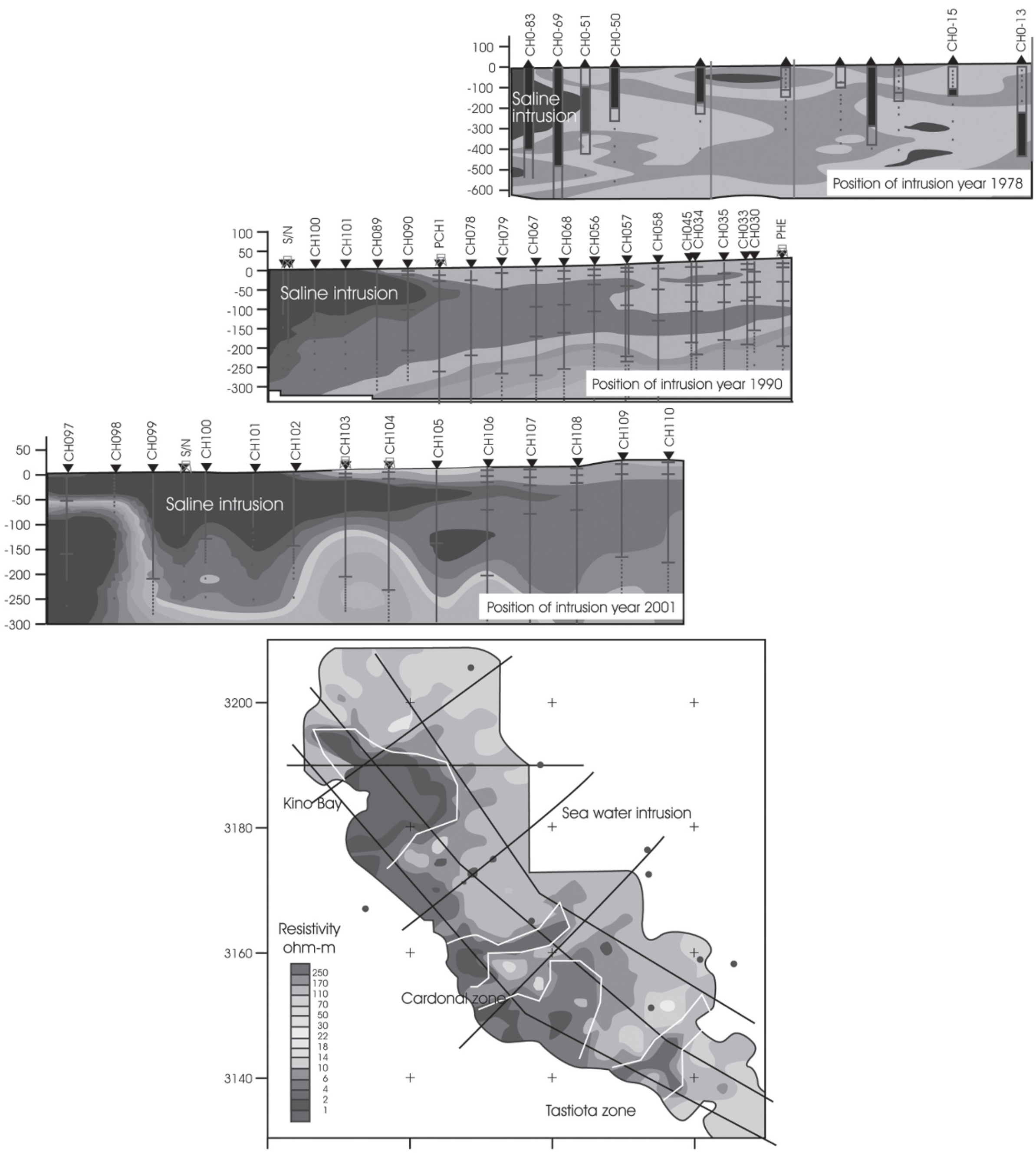


5.8 Conclusions

The Puerto Peñasco aquifer contains a relatively small volume of brackish water in a thin wedge that rests on marine water north of the coastal strip, so it is not suitable for the extraction of large volumes of brackish water. In any case, the extraction of brackish water is a delicate operation and the discharges must be carefully controlled using data obtained with hydrochemical analyses. It is crucial to continually monitor water quality, as any excessive pumping could cause upwelling of the marine water underneath.

An aquifer such as the Costa de Hermosillo that was operated for 20 years after the first wells were

Figure 5.11: Evolution of marine water intrusion in the Costa de Hermosillo aquifer. **Source:** Designed by the authors based on their research.



drilled without technical supervision under a national policy of colonization, within a legal framework that supported the drilling of wells, and was subjected to intensive pumping for the next 32 years using a mistaken hydrogeological model, could not have results very different from those presented in this chapter. The recovery of the aquifer is expected to be slow, expensive, difficult, and probably largely irreversible. It is understood that the water supply cannot simply be stopped suddenly, leaving the agricultural users without the vital liquid. Currently, in the lower basin of the Sonora River, the city of Hermosillo has a rapidly growing water demand, due to the expansion of the population. Therefore, as Dourejeani and Jouravlev (2003) stated, the solution of problems should be *integral*, without de-linking of the improved management of water resources and basins where water is captured.

An approach to be followed by administrators for the management of any coastal aquifer should include three main factors: control, prevention and remediation. In the case of the aquifers treated here, the first two were overtaken by events. For the third element, the most important actions can be summarized as: (a) reorganization of the extraction, (b) integrated use of water resources, and (c) engineering works for restoration (dams, concrete curtains, artificial recharge, etc.) (Tulipano, 2003). Actions (a) and (b) require that there should be order and authority *at the beginning of* the exploitation of an aquifer. The regulatory institutions and users should establish rules of operation under the criterion of sustainable extraction. The third action (c), enforces a restoration plan that depends on the comprehension and cooperation of the users of the water resources. Only in this way will it be possible to effectively reorganize the policy and practice of aquifer extraction and, consequently, the integrated use of the whole basin. Otherwise, any management policy will be useless and the deterioration of the natural environment will continue, as has been the case up until now.

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6 Preliminary Investigation of Groundwater and Surface Water Geochemistry in Campeche and Southern Quintana Roo

Eugene Perry, Guadalupe Velazquez Oliman and Niklas Wagner

6.1 Introduction[1]

This study of the hydrogeology of Campeche and southern Quintana Roo complements an earlier study of the northern part of the Yucatan peninsula. In the most north-western part of Campeche state, stratigraphy of aquifer rocks is continuous with that of adjacent Yucatan state, and groundwater geochemistry of chloride, sulphate, and strontium ions indicates that the major ion source for water wells of the city of Campeche is an underlying saline intrusion that is continuous with the intrusion in the western part of Yucatan state. Elsewhere in Campeche state and east of 90° 45' West (longitude of Escarcega), there is little or no geochemical evidence for a saline intrusion. In much of the southern part of the state, groundwater ion chemistry is dominated by dissolution of extensive beds of gypsum/anhydrite-bearing evaporite of probable Palaeogene age that releases sulphate and chloride ions to the aquifer. The evaporite also releases minor amounts of strontium, which is a useful tracer even at low concentration. This strontium apparently comes from the dissolution of the mineral celestite ($SrSO_4$), which appears to be ubiquitous (although not abundant) in evaporite beds. Evaporites are also the major ion source for most of the groundwater of the southernmost part of Yucatan state and southern Quintana Roo. Groundwater in and near the valley of the Rio Hondo (along the Mexico-Belize border) has high concentrations of sulphate and strontium but unusually low concentrations of chloride. The ratio of sulphate to chloride and the ratio of (Sr)/(Ca) versus 1/(Sr) are used here to evaluate ion sources of all samples in this study. Persistent clay is present in the lower Palaeogene rocks of southern Campeche. The clay units are highly impermeable, and they are capable of effectively isolating surface water from the sulphate-rich groundwater of the aquifer. The result is the formation of a large number of ponds, pools, and abandoned water-filled stream valleys, at least some of which contain water of exceptionally low ion concentration (in marked contrast to the sulphate-rich water of adjacent wells). This surface water may be a suitable source of potable water for communities in the area.

This study contributes to the understanding of water-rock interaction in the southern Yucatan peninsula. Identification of ion sources for the aquifer system is an important tool for water management in Campeche and Quintana Roo. Here we extend recently published research on the groundwater geochemistry of the northern Yucatan peninsula (Perry et al., 2009) into Campeche and southern Quintana Roo. Relevant details about regional hydrostratigraphy and methods of data acquisition and interpretation can be found in that paper and are only briefly summarized here. In particular, table 3 of Perry et al. (2009) describes the importance to hydrogeology of regional geological features including 'layer cake' carbonate stratigraphy, lack of surface drainage, importance of fault and fracture systems in channeling groundwater movement, contribution of the Chicxulub impact crater to stratigraphy and structure, importance and extent of a marine saline intrusion, and the value of evaporite beds and the spatially (and perhaps genetically) related impact of ejected layers as geochemical tracers.

Several geological formations present in Campeche are continuous with those of the north of the Yucatan peninsula; but folding is more common

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Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_6,

in the south; topographic relief is greater; some streams, wetlands, and lakes are present; and distinctive closed basins of various sizes, mapped as poljes, are important geomorphic features. The geology of south-eastern Campeche is complex and remains poorly studied (Schönian et al., 2005, 2008). A widespread geological unit, mapped as early Palaeogene (Servicio Geológico Mexicano, 2007), strongly influences groundwater geochemistry because it contains bedded evaporite consisting of gypsum and other relatively soluble minerals. Also, because of the high solubility of gypsum and other sulphate minerals, these beds, which may include impact ejecta and/or overlying evaporite beds of variable thickness, are poorly exposed. Their influence on hydrogeology is critical to this study, but knowledge of their full extent, thickness, and properties awaits detailed geological mapping.

6.2 Ions as Tracers in Yucatan Groundwater

There are two principal sources of ions in groundwater (and surface water) of the Yucatan peninsula; these are sea water from a major saline intrusion and dissolution of minerals from aquifer rocks. The inorganic ions that are most important in Yucatan groundwater geochemistry include HCO_3^-, CO_3^{-2}, Cl^-, SO_4^{-2}, HS^-, Na^+, K^+, Ca^{+2}, Mg^{+2}, and Sr^{+2}. Sources and sinks for these ions are listed in Perry et al. (2002). Most of them are not useful in tracing natural ion sources on a regional scale because they (1) may have an anthropogenic source, (2) are present in similar abundance throughout the peninsula, or (3) are highly reactive and hence responsive to particular local environmental factors such as redox conditions and ion exchange reactions. Here we shall consider primarily abundance relations between the relatively conservative ions chloride, sulphate, and strontium as groundwater tracers. There is an additional advantage in using strontium as a tracer of ion sources. Its isotopic ratio ($^{87}Sr/^{86}Sr$) is often specific to a particular stratigraphic unit (Perry et al., 2009).

In northern Yucatan and Quintana Roo, sea water, modified by interaction with aquifer rock, penetrates far inland beneath a layer of less dense fresh water (Perry et al., 1989, 1995; Marin, 1990, 2007; Marin et al., 2000; Escolero, 2007; Escolero et al., 2000, 2002, 2005, 2007). Although the distance to which this intrusion penetrates has not been established, its presence near Santa Elena at UNAM5 (figure 6.1), more than 80 km from the coast of the Gulf of Mexico, has been documented (Perry et al., 2002).

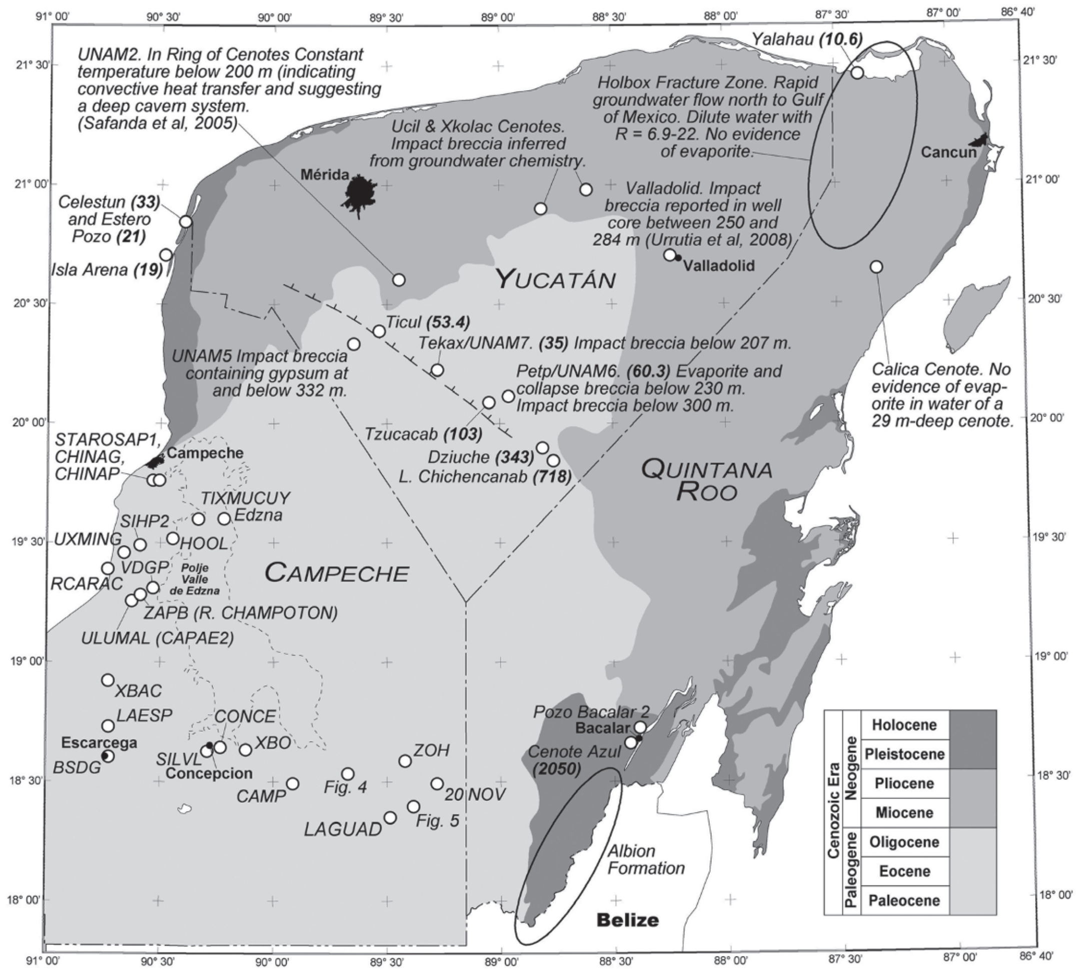
Furthermore, there is a strong indication that sea water penetrates inland and establishes a counter-flow to fresh water movement through the permeable zone of the Ticul Fault at least as far inland as Tzucacab and Dziuche (Perry et al., 2009). The presence of this saline intrusion has important practical consequences. It establishes subsurface counter-currents and affects fresh water quality by mixing and/or upcoming in excessively pumped wells (Beddows et al., 2007; Escolero et al., 2002, 2007; Perry et al., 2002, 2009; Steinich/Marin, 1997; Stoessell et al., 1989).

Where a saline intrusion is present it contributes to the geochemistry of the overlying fresh groundwater by turbulent mixing. That contribution can be estimated from the chloride content and the ratio of the normally conservative ions, Cl and SO_4 (Perry et al., 1995, 2002; Escolero et al., 2005). The ratio of these two ions in sea water, expressed for convenience as $100[(SO_4)/(Cl)]$ (henceforth R) and measured in equivalents, is about 10.3. Groundwater beneath much of northern Yucatan and Quintana Roo has a relatively high concentration of chloride, and it has R values close to 10, suggesting that its chemistry is strongly influenced by interaction with the underlying saline intrusion (Perry et al., 2002).

R can be modified by chemical reaction, dissolution of aquifer minerals, or adsorption. Chloride is highly conservative – it has little tendency to interact chemically with the rocks of the aquifer. Although water will readily dissolve the highly soluble mineral halite (NaCl), that mineral is unlikely to persist in the permeable, well-washed rocks of the Yucatan aquifer except perhaps as inclusions in other less soluble minerals. Sulphate ion is less conservative than chloride. Its concentration in groundwater can increase if the aquifer contains gypsum ($CaSO_4 \bullet 2H_2O$), anhydrite ($CaSO_4$), or celestite, $SrSO_4$. Conversely, sulphate concentration decreases if redox reactions in the aquifer convert sulphate ions to sulfide.

In previous research studies of Yucatan groundwater we have found it useful to compare strontium concentration to chloride and sulphate concentrations. Strontium, which can easily be analyzed at low concentrations, is the essential cation in celestite ($SrSO_4$). It is also a minor ion in calcite, dolomite, and gypsum; and although aragonite can contain up to 7000 ppm, that mineral is uncommon except in the youngest carbonate rocks along the coastal fringe of the peninsula. Celestite is not abundant, but it appears to be ubiquitous in evaporite rocks of the peninsula.

Figure 6.1: Sites of sampling. **Source:** Research data on the geology and hydrogeology of the Yucatan peninsula. Location of sampling sites for this paper in Campeche and southern Quintana Roo are shown. Also shown are specific aspects of the hydrogeology of the northern peninsula. Unless indicated, these summarize information in Perry et al. (2009). Numbers in parentheses within sample bullets are R values for water samples from lakes and municipal wells [R = 100[(Sr)/(Cl)] in meq/kg].



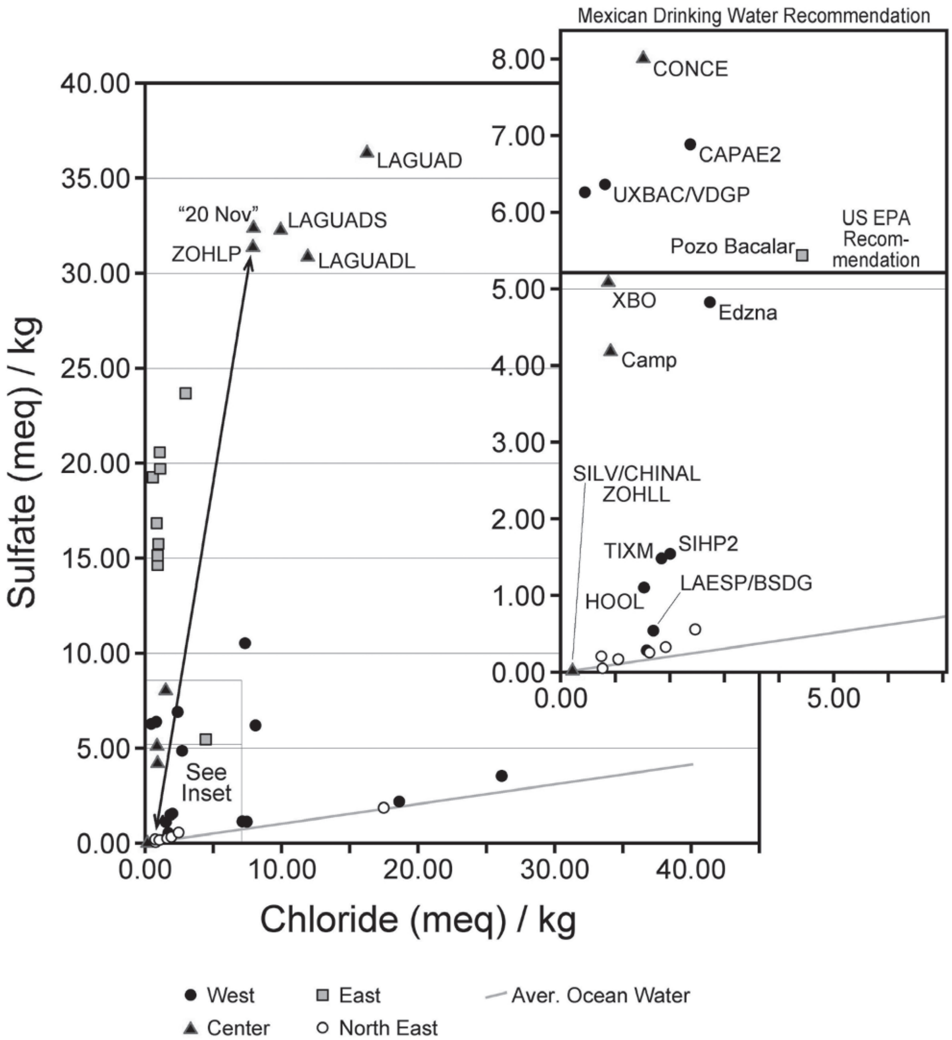
Groundwater that comes into physical contact with evaporite therefore may locally equilibrate with celestine, which can then control its strontium ion content. Perry et al. (2002, 2009) have presented evidence that the concentration of strontium in Yucatan groundwater is a reliable indicator of evaporite in the subsurface.

6.3 Chloride and Sulphate Ions in Groundwater of Campeche and Southern Quintana Roo

Our study of groundwater geochemistry of Campeche east of 90° 45' W (longitude of Escarcega, Campeche) indicates that a saline intrusion is limited to the north-west corner of the state and to a narrow coastal fringe. All of our samples from southernmost Quintana Roo have high R values and exceptionally low chloride concentrations. Together with strontium data presented below this indicates the lack of a saline intrusion over most of the area covered by this study (figure 6.1, 6.2; table 6.1). Four groundwater samples from north-west Campeche do show geochemical evidence of sea water influence.

RCARAC is from the shallow well on the property of a beachfront restaurant, less than 100 m from the Gulf of Mexico. The other samples from near the western (Gulf) coast that have R ratios of 12 to 16 (approximating that of sea water) are STAROSAP1, CHINAP and CHINAG (figure 6.2). On the basis of their strontium composition, each of these water sam-

Figure 6.2: Sulphate *vs*. chloride concentration. **Source:** Research data. Units on axes are in meq/kg. Diagonal line emanating from the origin is the sulphate/chloride ratio in sea water. Inset is a 'blow-up' of the origin. Samples within the smaller box are within US EPA recommended limits for drinking water. (Mexican recommended limit for sulphate in drinking water is 400 ppm (8.1 meq/kg)). Double arrow indicates surface water and well-water concentrations from the same town. Sites labelled 'West' are from near the city of Campeche and the Valle de Edzna. Those labelled 'Centre' lie along or near Mexican Highway 186. Those labelled 'East' are from near the Rio Hondo (Mexico-Belize border).



ples probably also contains water from a third recharge source as is discussed in the section on strontium ion chemistry. STAROSAP1, CHINAP and CHINAG, which are water supply wells for the city of Campeche, all meet the Mexican drinking water norm for sulphate.

Rio Champoton, which enters the Gulf at the town of Champoton, drains the polje Valle de Edzna (figure 6.1). It is represented by sample ZAPB, which has a high strontium content and an R value of 72 and thus, except for a relatively high chloride content of 7.3 meq/kg, shows no indication of interaction with sea water even though the sample was taken within about 15 km of the Gulf coast.

Water from well BSDG in Escarcega, the fourth most populous city in Campeche, has an R value of 31.6 and exceptionally low concentrations of chloride and sulphate (figure 6.2). The R value, which is only about three times that of sea water, could indicate a sea water component; however, on the basis of its low chloride and its strontium ion chemistry we consider it to have a different mixing history, as discussed

Table 6.1: Chemical data and probable ion sources for groundwater and surface water of Campeche and Southern Quintana Roo. **Source:** Data from research.

Name	Lat/Long	Cl (meq/l)	SO_4 (meq/l)	R (meq/kg	1/Sr (mmoles)	1000Sr/ Cl (moles)	Probable Source(s)	Criteria
CHINAGF	19.77/90.50	7.49	1.12	14.98			S	R
CHINAG	19.77/90.50	7.16	1.14	15.91	91.13	1.53	S, D, E	R, Sr
STAROSAP1	19.74/90.54	18.62	2.17	11.66	49.46	1.09	S, D, E	R, Sr
EDZAARQ	19.60/90/23	2.73	4.83	176.98	34.29	10.68	D, E	Sr
TIXM	19.58/90.32	1.86	1.49	80.54	86.75	6.21	D, E	Sr
SIHP2	19.50/90/58	2.02	1.55	76.35	49.50	9.98	D, E	Sr
HOOL	19.50/90.45	1.54	1.10	71.75	105.95	6.13	D, E	Sr
UXMING	19.48/90.66	8.11	6.15	75.86	20.54	6.00	S, E, D	Sr
RCARAC	19.41/90.72	26.12	3.52	13.50	42.59	0.90	S, D, E	R, Sr
ZAPB	19.28/90/61	7.34	10.52	143.37	8.71	15.64	E	Sr
VDGP	19.27/90.46	0.82	6.35	772.70	11.91	102.26	E	Sr
CAPAE2	19.26/90.62	2.40	6.87	285.59	15.30	27.18	E, D	Sr
XBAC	18.94/90.73	0.46	6.25	1355.76	30.30	71.63	E, D	Sr
LAESP	18.74/90.73	1.59	0.27	17.05	379.31	1.65	D	
Bacalar P2	18.73/88.44	4.47	5.42	121.29	22.82	9.80	E, D	Sr
VLAG	18.66/88.41	2.98	23.67	794.80	10.99	30.54	E	Sr
XBO	18.64/90.17	0.89	5.13	579.39	6.24	180.86	E	Sr
SILVL	18.63/90.29	0.20	0.04	19.52			Rain	
CONCE	18.62/90.13	1.54	8.01	519.59	6.37	101.84	E	Sr
BSDG	18.62/90.74	1.71	0.54	31.63	73.02	8.01	D, E	Sr
ZOHLP	18.60/89.42	7.90	31.49	398.62	11.18	11.33	E	Sr
ZOHLL	18.59/89.42	0.23	0.03	12.92	2037.67	2.13	Rain	
CAMPAGUD	18.48/89.89	0.93	4.22	451.98	74.86	14.32	D, E	Sr
"20NOV"	18.45/89.31	7.95	32.50	408.65	8.94	14.06	E	Sr
Palmar Spr	18.44/88.53	1.09	20.57	1880.82	10.83	84.42	E	Sr
Palmar HR	18.44/88.53	0.87	16.85	1928.01	16.11	71.04	D, E	Sr
ACAD	18.43/88.53	1.14	19.73	1737.15	11.31	77.88	E, D	Sr
RdelToro	18.35/88.60	0.91	14.66	1607.41	14.25	76.96	D, E	Sr
SpringRanch	18.35/88.60	0.91	15.12	1664.42	14.48	76.02	D, E	Sr
LAGUAD	18.33/89.48	16.29	36.46	223.87	5.42	11.33	E	Sr
LAGUADL	18.33/89.48	11.92	31.00	260.15	9.14	9.18	E	Sr
LAGUADS	18.33/89.48	9.93	32.41	326.21	10.89	9.24	E	Sr
Cocoyol HR	18.17/88.68	0.55	19.26	3515.88	21.48	85.00	D, E	Sr
Cocoyol Well	18.16/88.69	1.00	15.71	1571.57	11.28	88.70	E, D	Sr

Notes: Sources: S = Saline intrusion; E = Evaporite; D = Dilution by water normal karst groundwater. Criteria: R = [100(SO_4)/Cl)]; Sr = Position on figure 6.3.

below. UXMING, with an R value of 38, may have a sea water component. Its composition is also discussed further below with respect to its strontium chemistry.

A traverse westward from Escarcega to Chetumal along Mexican Highway 186 encounters groundwater with sulphate concentrations deemed too high for acceptable drinking water (figure 6.2). This is the result of dissolution of sulphate from beds of Palaeocene gypsum (figure 6.4) such as those exposed to surface weathering east of Concepcion, Campeche state (labeled CONCE in figure 6.1).

Because all the water encountered in wells drilled in eastern Campeche has an exceptionally high sulphate concentration, CONAGUA has installed an aqueduct to deliver water to Xpujil from wells near Concepcion. Representative municipal well samples from the area include ZOHLP and '20 NOV', which have almost four times the Mexican recommended maximum value of 400 ppm (8.3 meq/kg) for drinking water (figure 6.2). One of three samples from the vicinity of La Guadalupe (LAGUAD on figure 6.1) contains more than 36 meq/kg (1750 ppm) of sulphate.

6.4 Groundwater from Northwestern Quintana Roo

In order to present a complete survey of groundwater geochemistry of the Yucatan peninsula we present here analyses of a suite of samples from the Holbox Fracture Zone in the farthest north-eastern part of Quintana Roo (figure 6.1; Tulaczyk et al., 1993). These data are instructive because they illustrate the characteristics of dilute groundwater in a region of high recharge in which the water chemistry is dominated by a saline intrusion. All of these samples have R values between 7 and 26, with an average of 16. Although this value is high compared to the sea water ratio of 10.3, these waters are very dilute and hence readily subject to contamination by surface processes. The largest spring, Yalahau (figure 6.1) has an R value of 10.6 and may be sampling a representative part of the aquifer. We tentatively conclude that, in contrast to the waters of Campeche, these waters have a simple history and derive most of their ion content from sea water.

6.4.1 Strontium Ion as a Groundwater Tracer

A useful groundwater and surface water geochemical diagram is one in which the ratio 1000 [(Sr)/(Cl)] is plotted on a logarithmic scale vs. the reciprocal of strontium concentration. In a diagram of this kind, binary mixtures of two waters differing in their strontium and chloride concentrations plot along straight lines.[2] Figure 6.3 is a strontium/chloride plot of data of this study (listed in table 6.1). For comparison, figure 6.3 also includes data from the adjoining region, Yucatan state and northern Quintana Roo, which were published by Perry et al. (2009). Comparison of the two data sets is especially helpful because, whereas we do not yet have strontium isotope data for the samples in table 6.1, strontium isotope analyses were available to help identify mixing trends in the earlier data set from Quintana Roo and Yucatan State (Perry et al., 2009).

The inset in figure 6.3 shows various mixing trends for a water, X_1, in chemical equilibrium with an evaporite that contains gypsum, celestite, and some trapped inclusions of highly soluble halite (NaCl), the latter acting as a source of chloride ions. Because of its high strontium concentration, water X_1 will occupy the left-hand side of the diagram. Mixtures of X_1 with waters A or B will appear as straight lines (X_1A, X_1B). Mixtures along path X_1C are more difficult to explain because they would imply existence of a water of composition C, which was otherwise dilute but that had a high content of strontium. One way of moving along path C would be to have a dilute water that flowed continuously over an evaporite, washing away its most soluble phases such as halite. Alternatively, the evaporite unit corresponding to C may have a different composition (higher in NaCl) than the unit at X_1. This is not a hypothetical question; it involves how to best interpret actual samples from south-western Quintana Roo that appear in the upper left corner of figure 6.3.

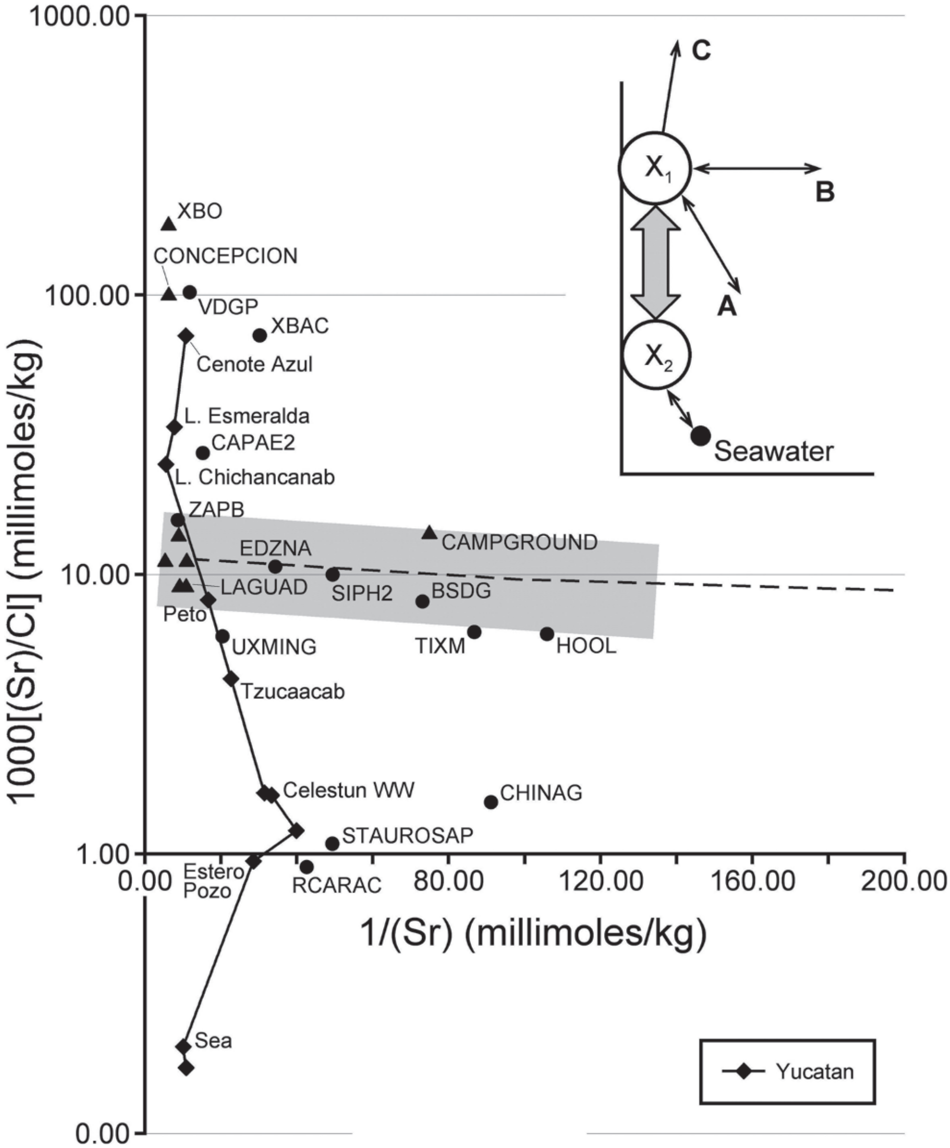
Note that the composition of water X depends on the origin of the water that maintains contact with the evaporite. For example, if evaporite is present in the part of the aquifer within the chloride-rich saline intrusion, the resulting water will occupy a position on the diagram similar to X_2. This is the case of water from Xkolac and other deep cenotes shown in figure 6.2 of Perry et al. (2009). For further discussion of the behaviour of water in deep cenotes, readers are referred to that paper.

6.4.2 Evaluating Inorganic Ions

From figure 6.3 it is apparent that STAUROSAP1 and RCARAC are very similar to the coastal waters Celestun WW, Estero Pozo, and El Remate (Perry et al.,

2 Note that in this plot of 1/(Sr) the samples with the highest strontium concentration plot nearest the origin.

Figure 6.3: Sulphate *vs*. chloride concentration. **Source:** Research data. Vertical axis is 1000[(Sr)/(Cl)]. Horizontal axis is 1/(Sr). Both axes are in units of millimoles/kg. On this plot, mixtures of two waters plot along a straight line. Labels as in figure 6.2. In addition, diamonds are samples from Yucatan state and northern Quintana Roo (taken from Perry et al., 2009).



2009). The hydrogeology of those waters from the earlier study is instructive. Each is a coastal well near the terminus of the major underground flow system running along the Ticul Fault and the western arm of the Ring of Cenotes (Perry et al., 2009) that is marked in figure 6.1. That shows the progressive change in sulphate/chloride ratios as that evaporite-laden water moves north-west from Lake Chichancanab toward the Celestun estuary. The straight mixing line between water samples from L. Chichancanab and Celestun WW in figure 6.3 passes through water samples from the municipal water supplies in Peto and Tzucacab. These are all waypoints for water originating in the vicinity of the lake and moving through the Ticul Fault system and the Ring of Cenotes. As it flows northwestward, this water mixes with other groundwater and with the underlying saline intrusion. By analogy with the waters from Yucatan state, STAUROSAP1 and RCARAC can be seen from figure 6.3 to be three-way mixtures of sea water, dilute groundwater, and water draining an evaporite terrain. Also, UXMING lies along a mixing path (like path A in the schematic of figure 6.3) that is identical to the mixing line connecting water from Celestun WW and Peto in Yucatan.

Samples HOOL, BSDG (supply well for Escarcega), SIPH2, EDZNA, TIXM, and CAMP lie on or near a mixing line shown as a dashed line in figure 6.3, which connects dilute lagoon water ZOHLL and highly concentrated evaporitic water from the adjacent well ZOHLP. This path is analogous to path B in the schematic of figure 6.3.

Compared to groundwater from the north-eastern and north-central peninsula, water from that part of southern Quintana Roo along the escarpment of the Rio Hondo that borders Mexico and Belize has high strontium and sulphate and exceptionally low chloride concentrations (figures 6.2, 6.3). Samples of this suite are from 1) springs debouching metres to tens of metres above the Rio Hondo valley floor, 2) municipal wells, and 3) the Rio Hondo itself. In addition, one sample is from Lake Bacalar. These samples are all similar in composition to water from Cenote Azul, sampled previously (Perry et al., 2009). They appear to be effectively isolated from sea water and hence indicate the absence of a saline intrusion. That observation is strengthened because Cenote Azul, which is near the coast (figure 6.1) is at least 65 metres deep, yet its water is constant in composition and exceptionally low in chloride over the entire depth range. These samples follow path X_1C in the schematic diagram in figure 6.3. The precise reason that water in close contact with evaporite should vary is not possible to determine from data available at this time. It is important to note that whatever the exact mechanism, these samples have not exchanged with sea water or with a saline intrusion.

Bacalar Pozo 2, a water supply well for the town of Bacalar, is several km north-west of the town (figure 6.1). It does not evidence the same degree of strontium enrichment/chloride depletion shown by other samples of the eastern sample suite.

Several samples in south-central Campeche come from wells that are exceptionally high in sulphate. LAGUAD and LAGUADL are from shallow dug wells within the town of La Guadalupe. They are severely contaminated as indicated by nitrate concentrations of 4 and 8 meq/kg respectively. A nearby spring (LAGUAD) flows out from an outcrop of gypsum. ZOHLP and '20 NOV' are nearby municipal pumping wells. Gypsum and anhydrite outcrops are common in this area (figure 6.4), and sulphate in water here is sufficiently objectionable for drinking that CONAGUA has installed an aqueduct to provide potable water to part of the area.

Note that water from these wells contains significantly more chloride than water from the Rio Hondo region. It seems likely that the evaporite here contains an appreciable amount of halite as inclusions protected from dissolution until it is released when surrounding crystals of gypsum dissolve.

6.5 Perched Water Table

Extensive layers of clay are present in southern Campeche and southern Quintana Roo, and these act effectively as aquitards, trapping meteoric precipitation in ponds and lakes throughout the region. The largest of these is Lake Silvituk (SILV: figure 6.1; table 6.1) with chloride and sulphate concentrations respectively of 0.2 and 0.04 meq/kg, yielding a near-sea water R value of 9.8[3]. Water from another small lake illustrates the sealing value of the local clay aquitard. Sample ZOHLL is from a lake on the edge of the small town of ZOH. Its water has among the lowest concentrations of sulphate (figure 6.2), yet water from the municipal well, ZOHLP, has one of the highest sulphate values encountered in this study.[4]

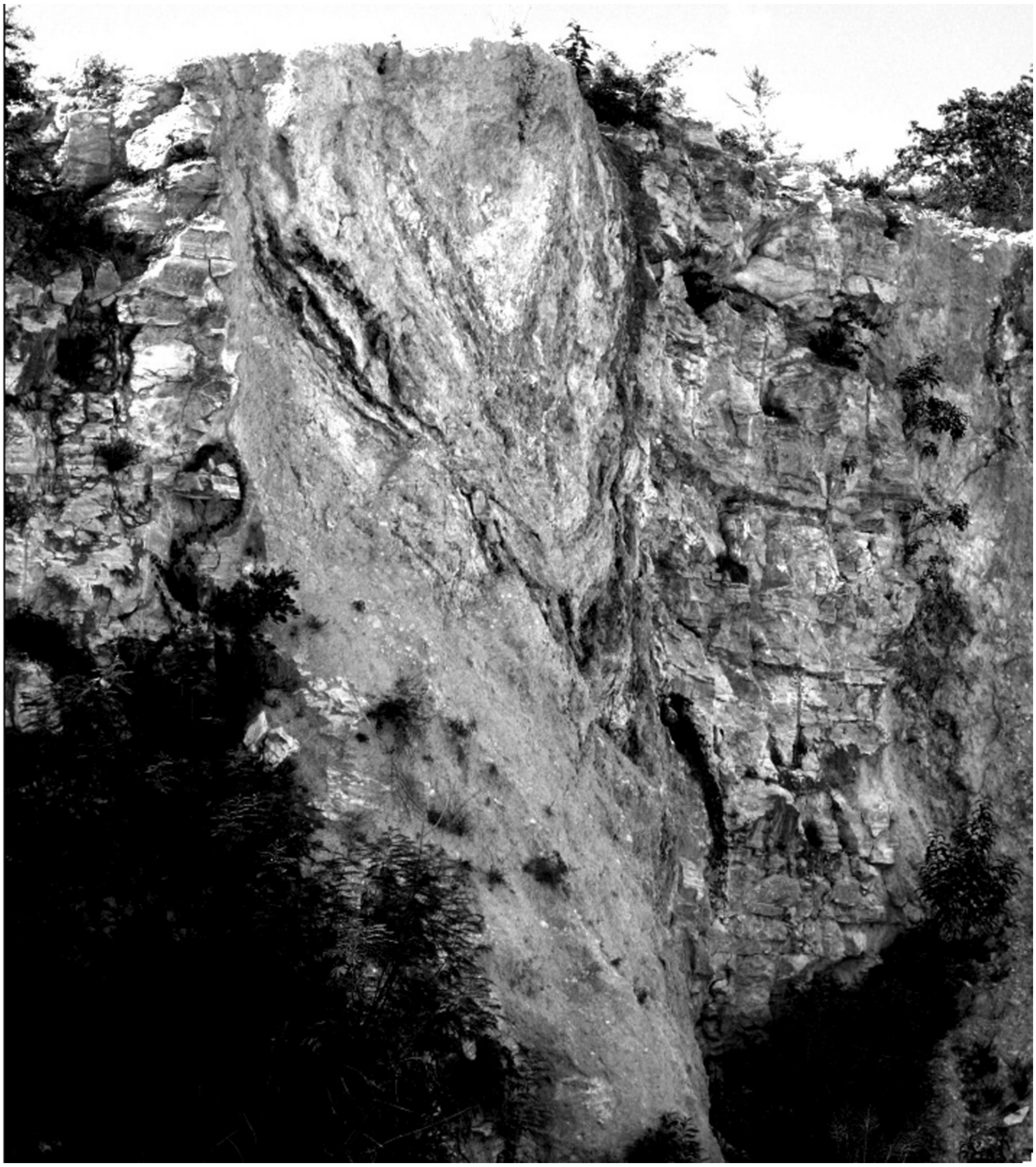
6.6 Suggestion for Further Investigation

Adequate drinking water of desirable quality is difficult to obtain in eastern Campeche. Drilling has not encountered water of low sulphate content. However, this area has a unique system of internal streams and ponds supported by one or more layers of highly impermeable clay (one or more of which may have developed from lapilli of K/Pg impact ejecta (Schönian et al., 2005, 2008)). Figure 6.5 shows one example of a lake that once was a meandering stream. Our results show that this surface water can be of very good quality (figure 6.2). In a region with 1,200 mm of annual rainfall, it may be useful to evaluate the possibility of developing this surface water as a resource in this region with a growing population.

3 It is much more likely that this R value is the result of atmospheric transport or even coincidence than that it is produced by contact with a saline intrusion.

4 Even the nitrate content of the three surface water bodies sampled was below the limit of detection, presumably because available nutrients were consumed by plant growth.

Figure 6.4: Bedded gypsum outcrop about 20 m high on highway 186 east of Concepcion, Quintana, Roo (CONCE in figure 6.1). **Source:** Photo from research of the authors.



This pond occupies a meandering channel apparently vacated by a stream as a result of drop in the water table. Closed internal basins drained from below (mapped as poljes) are common in this area. Whereas groundwater has uniformly high sulphate content, lakes and ponds from here tend to have water with low salinity.

6.7 Summary and Conclusions

This study has determined the major ion sources for a large and developing region whose complex geology and hydrology have received little study. The ion sources for a representative suite of water samples analysed for this study have been discussed in detail. In table 6.1, we have specified the probable major ion sources for all water in the study, and we have listed there the criteria that led us to those conclusions.

A saline intrusion extends south from Yucatan state into the north-west corner of the state of

Figure 6.5: A pond in southern Campeche (located in figure 6.1). **Source:** Photo taken during the authors' research.

Campeche. Near the city of Campeche the fresh water aquifer is likely to be underlain by a saline intrusion. This intrusion does not extend far south of the city of Campeche. Figure 6.2 shows that potable water is present in and around the Valley of Edzna, but east of Concepcion, Campeche; groundwater is heavily contaminated by sulphate ion contributed by extensive evaporite deposits. Dissolution of evaporite also dominates groundwater geochemistry along the Rio Hondo in southern Quintana Roo.

It is unlikely that groundwater of good quality will be found in eastern Campeche. However, the occurrence of abundant beds of impermeable clay in that region suggests that it may be possible to exploit natural surface water sources and to develop new surface sources of good quality there.

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Part II Water Use, Availability and Alternative Sources

Chapter 13 Evapotranspiration in the Upper and Middle Nazas River Basins

Eduardo Chávez Ramírez, Guillermo González Cervantes, José Luis González Barrios and Alejandro López Dzul

7 Environmental Monitoring and Crop Water Demand

Jaime Garatuza Payán, Julio Cesar Rodríguez and Christopher J. Watts

7.1 Introduction[1]

Environmental monitoring refers to a stream of measurements and observations of the different characteristics of the natural environment. It could be made up of measurement systems of different components of natural systems, evaluation of parameters related to air quality, meteorology, quantity and quality of soil and water, and so on. One of the most important applications of meteorological and vegetation monitoring is the determination of crop water requirements or consumptive use. All vegetation consumes water in transpiration and this process is closely linked to photosynthesis. Direct evaporation also converts liquid water to vapour and it is usual to lump both together as *evapotranspiration* (ET).

The estimation of crop water requirements or ET is a very important part of water management in agriculture, regional water balance studies and hydrological modelling. It is possible to measure ET but the methods are complicated and costly, so that it is usually estimated using mathematical models. The method most commonly used for estimating ET in irrigated crops consists of defining a reference value (ET_0) which represents the atmospheric demand (potential ET) and multiplying this by a crop factor (Kc) which characterizes the state of the vegetation. Reference ET (ET_0) refers to ET from a reference crop that is plentifully supplied with water, and is usually obtained using some version of the Penman equation using meteorological information from a nearby climate station. The crop factor can be obtained from tables in which its value is related to the development stage of the crop. In order to obtain a good estimate of Kc, these values should be calibrated using local data. Nowadays, monitoring of vegetation condition can be conveniently carried out using sensors on board various spacecraft (Earth Observation Satellites), so that it should be possible to estimate the crop factor using spectral vegetation indices.

This chapter includes more than 10 years of studies in north-west Mexico, where measurement campaigns have been conducted for wheat, cotton, safflower, sorghum, potatoes, beans, chili, grapes and pecans using the aerodynamic method or 'eddy covariance'. In this way crop factors have been obtained for a wide variety of crops, which were then related to vegetation indices derived from satellite data at diverse spatial, spectral and temporal resolutions. Results show that it is possible to map ET over large areas (e.g. an entire irrigation district) using standard meteorological data from the network of climate stations together with remotely sensed data from satellites.

Environmental monitoring refers to a system for continuous observation and measurement of characteristics of the natural environment, allowing the evaluation of the observed changes and forecasts of future ones. During the 1960s, the severe environmental deterioration in many parts of the world was finally recognized, and with it, the need for records of environmental observations, and this led to the establishment of several environmental networks (Meadow et al., 1972). These monitoring systems cover different components of the environment: atmosphere, biosphere, hydrosphere and lithosphere, monitoring variables such as air quality, water and soil (quantity and quality), and many others.

Specifically, among the main hydroclimatological and vegetation monitoring objectives is the use of data for crop water needs assessment, in order to attain more efficient water use and better natural resources management. The aim of this work is to demonstrate that it is possible to monitor water use by vegetation (including crops) in real time, combining remotely sensed images with data from hydrometeorological networks. The micrometeorological group at the *Sonora Institute of Technology* (ITSON) and the *University of Sonora* (UNISON) started to work to-

1 Keywords: Evapotranspiration, remote sensors, crop factor, vegetation index.

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_7,

gether about 15 years ago and results from this period are presented here.

7.2 Meteorological Networks

Atmospheric and meteorological measurements have a long history in Mexico, going back several centuries. More recently, the *National Meteorological Service* (SNM) was established in 1901 with its own meteorological observatories and stations transmitting climatic data by telegraph. Afterwards, SMN was absorbed by the *Ministry of Water Resources* (SRH) and now is part of the *National Water Commission* (CONAGUA). An important responsibility of SMN is to maintain a national database and provide public access to meteorological and climatic information, as well as the realization of other meteorological and climatic studies. Thus, the infrastructure maintained by SMN includes more than 3000 meteorological stations, mostly manual, but including some automated stations.

Given the importance of hydrometeorological monitoring for agricultural activities and food production in Mexico, the federal *Ministry of Agriculture* (SAGARPA) has implemented a national network of agro-climatological stations, providing real-time meteorological data to help the agricultural sector and so improve the competitiveness of agribusiness. This network provides information to support farmers in improving their production, specifically in the application of irrigation water. The network contains more than 850 stations situated throughout Mexico.

7.3 Remotely Sensed Data

The constellation of *Earth Observation Satellites* (EOS) constitutes another system for environmental monitoring. These satellites carry diverse sensors that make continual observations of the earth (without the need to be in direct contact with it) in different regions of the electromagnetic spectrum. The observations consist of measurements of the energy reflected or emitted by objects on the earth's surface, or above it (clouds). The interpretation of these measurements is based a) on the distinctive spectral signature in which each object reflects the incident electromagnetic waves or b) on the quantity of energy emitted by the object as a function of its temperature, in accordance with the Stefan-Boltzmann law. Many different satellites and sensors have been used in environmental monitoring and table 7.1 shows a list (far from complete) of satellites and sensors in common use in Mexico. Three regions of the electromagnetic spectrum have been used most frequently: *visible* (VIS), *near infrared* (NIR) and *thermal infrared* (TIR). The minimum time between observations of the same site (temporal resolution) varies from 15 minutes to 26 days. The smallest surface that can be observed by a satellite sensor (spatial resolution) varies from 2 metres to 4 kilometres.

Table 7.1: Characteristics of the principal satellites or sensors with possible application in the estimation of water use by vegetation. PAN refers to a panchromatic broad band with high spatial resolution**. Source:** Data from the authors.

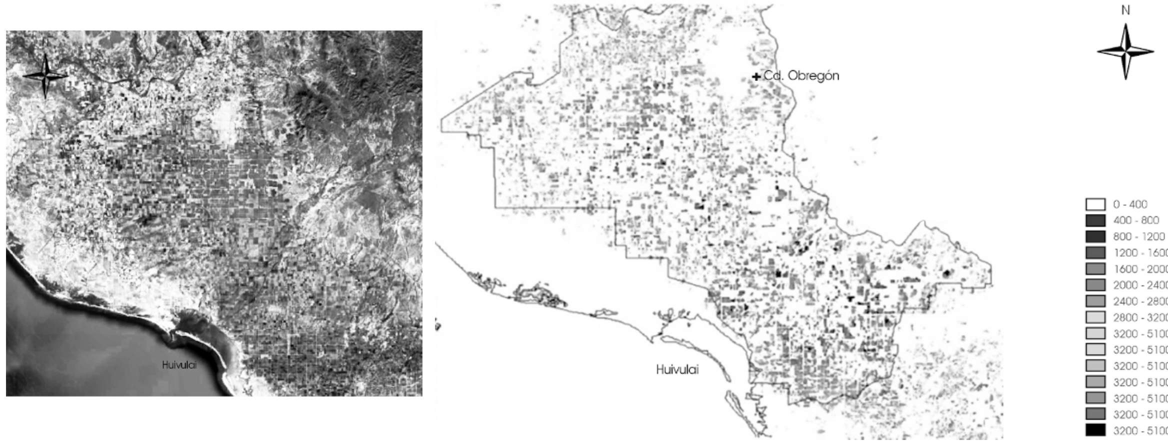
Satellite/ Sensor	Spectral Bands	Resolution	
		Spatial	Temporal
GOES	TIR	4 km	15 min
	VIS	1km	15 min
MODIS	VIS/NIR	250 m, 500 m	1-2 days
	TIR	1 km	1-2 days
Landsat	VIS/PAN	30 m / 15 m	16 days
	TIR	60 m	16 das
SPOT	VIS/PAN	10 m / 5 m	5-26 days
FORMOSAT	VIS/PAN	8 m / 2 m	3-5 days

Generally, in the context of water use by vegetation, satellite remote sensors are mainly used to estimate the photosynthetically active ('green') biomass present at a particular site and to estimate the difference between the temperature of the vegetation and the temperature of the surrounding air, since this difference is related to the concept of vegetation water stress. In order to monitor vegetation 'greenness', spectral vegetation indices are commonly used. The most common is the *Normalized Difference Vegetation Index* (NDVI; Rouse et al., 1974):

$$NDVI = \frac{(\rho_{NIR} - \rho_R)}{(\rho_{NIR} + \rho_R)}$$

where ρ_{NIR} and ρ_R are reflectance for the near infrared band and the red band, respectively.

Figure 7.1: a) Real colour composite and b) evapotranspiration (W m^{-2}) for wheat in the Yaqui valley, Mexico for one day during the growing season of 2000**. Source:** Landsat bands 1, 2 and 3.



7.4 Environmental Monitoring with Remote Sensors

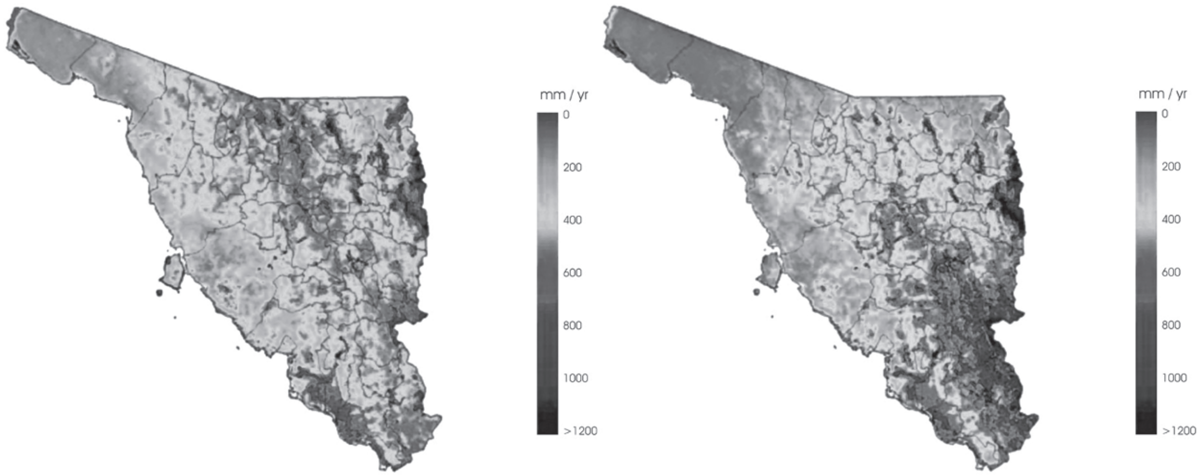
There are many examples of the use of remote sensing for environmental monitoring in Mexico. For example, Lobell et al. (2003) describe their experience using LANDSAT data to estimate wheat yields in the Yaqui valley, Sonora. Rodriguez et al. (2001, 2003, 2004) investigated the possibility of using MODIS data to forecast yields for 80 ha of wheat. Lobell and Asnar (2004) developed and tested a linear disaggregation approximation to estimate the fractional cover of different crops in one MODIS pixel, based on time series of spectral signatures during the growing season. They applied the technique in the Yaqui valley in Mexico and in the southern Great Plains in the USA, demonstrating the importance of sub-pixel heterogeneity in crop systems and the potential of temporal disaggregation for providing fast, reliable estimates of the spatial distribution of land cover using low spatial resolution images like MODIS.

Hudson and Colditz (2003) combined remotely sensed and geomorphic data to delineate the spatial extent of flooding in the lower Panuco River caused by a large hurricane in the Gulf of Mexico. Salinas-Zavala et al. (2002) analysed the relationship between the inter-annual variability of NDVI, rainfall and atmospheric circulation at 700 mb in northwest Mexico. They separated the data corresponding to the cold and warm phases of *El Niño Southern Oscillation* (ENSO) and found that the negative phase of ENSO was associated with drought conditions.

The application of remotely sensed data for estimating hydrological variables has a long tradition. In the early 1990s, Garatuza and Watts (1993) used VIS and IR data from the geostationary satellite GOES to estimate the extent of snow cover in the western Sierra Madre, and constructed a computational system for estimating other variables using GOES images provided by a receiving station installed at ITSON in Ciudad Obregon, Sonora (Stewart et al., 1995). These GOES images were used by Yucel et al. (1998) and Garatuza et al. (2001a) to obtain high resolution maps of cloudiness. Another application was the estimation of incoming solar radiation using GOES images from the receiving station at ITSON (Watts et al., 1995; Watts et al., 1999; Stewart et al., 1999; Garatuza et al., 2001b, 2001c). These studies provided new information about cloud cover in north-west Mexico and the use of this information in a new method of obtaining high resolution estimates for incoming solar radiation, an important variable in environmental monitoring for hydrological studies and integrated water management.

With regard to measurement, modelling, and estimation of evapotranspiration as an indicator of crop water requirements, various studies have been published (Garatuza et al., 1998, 2001d, 2003, 2005b; Garatuza and Watts, 2005; Mendez-Barroso et al., 2008; Unland et al., 1997), combining data collected in situ with remotely-sensed data of high and low spatial resolution (figures 7.1, 7.2). Additionally, experiments have been conducted to establish methods of estimating average surface fluxes over heterogeneous surfaces (Watts et al., 2001; Chehbouni et al., 2001, 2008).

Figure 7.2: Annual evapotranspiration in Sonora (a) October 1999 to September 2000 using NOAA-AVHRR images and (b) October 2002 to September 2003 using MODIS images. The outlines of municipal limits have been included. **Source:** Elaborated by the authors.



7.5 Crop Water Requirements

The estimation of crop water needs or *evapotranspiration* (ET) is an important issue in water management in irrigated agriculture, regional water balance studies and hydrological modelling. At the plot scale, estimates of ET are needed for irrigation scheduling and so form an integral part of decision support management tools (Abrahamsen/Hansen, 2000; Garatuza/Watts, 2005).

It is possible to measure the rate of ET in situ, but the equipment is expensive and the data collected in the field requires complicated processing procedures. For this reason, ET for irrigated crops is usually estimated as the product of reference ET (ET_0) that represents the 'atmospheric demand' and a crop coefficient Kc that reflects the vegetation condition (Garatuza/Watts, 2005):

$$ET = Kc * ET_0$$

where ET_0 refers to an "actively growing, well watered grassland (i.e. zero water stress) that completely covers the ground". ET_0 is usually calculated with some version of the Penman equation (Penman, 1948) that requires information about net radiation, air temperature and humidity, and wind speed. Unfortunately, many versions of this equation have been proposed and the method is sometimes not applied correctly, but the publication of FAO-56 (Allen et al., 1998) provides a convenient standardized version. So the correct estimation of ET requires the following data: characteristics and development stage of the crop, climate parameters, and management practices. The climate parameters are included in ET_0 while the others are included in the crop factor Kc.

7.5.1 Measurement and Estimation of Kc

The aforementioned factors are specific to each crop and change with crop development. Allen at al. (1998) subdivide the development stages of the crop into four phases: initial, development, stabilization and senescence, and presents tables with values of these coefficients for a large variety of crops, while recommending local calibration of the values. A great deal of work has been carried out to determine appropriate crop factors for different crops in different regions using different management practices. The determination of accurate estimates of Kc requires measurement of *actual* ET and the estimation (using climatic variables) of ET_0 so that

$$Kc = ET/ET_0$$

Some examples of the determination of Kc for different types of crops (annual, perennial, fruit trees, etc.) using different management practices (flood irrigation, drip irrigation, etc.) include Garatuza et al. (1998) who developed time dependent Kc for wheat and cotton under flood irrigation in the Yaqui valley based on *eddy covariance* (EC) measurements of actual ET; Benli et al. (2006), who used a weighing lysimeter to determine Kc for alfalfa in the semi-arid conditions of the Anatolian plains in Turkey; and Wanga et al. (2007), who used four different methods for measuring ET in an open pecan orchard to develop an equation for Kc as a function of effective vegetation cover. Hanson and May (2006) used the *Bowen Ratio Energy Balance* (BREB) method for estimating ET to obtain Kc for tomatoes under drip irrigation. They used a second-order relationship between Kc and vegetation cover, and developed curves describing the temporal variation of Kc for different sowing dates. Kang et al. (2002) used lysimeters to measure ET for wheat and corn in a semi-arid region of north-west China and developed a fifth-order polynomial relationship relating Kc to the number of days since sowing. Kjaersgaard et al. (2008) used EC to measure ET and net radiation measurements for ET_0 in a cold sub-humid region and found larger values for Kc than those previously used in that region. De Azevedo et al. (2007) used the BREB method for pineapples in tropical Brazil and found that Kc was dependent on the complex interaction of physiological factors and climatic conditions.

We can conclude from this list of examples – which is by no means exhaustive – that a great deal of effort has been made to determine crop factors all over the world, from cold to tropical climates; for a wide variety of crops, both perennial and annual; from complete soil cover to very sparse; from low crops to tall trees. Different management systems can be used for all of these and a wide variety of techniques are used to measure real ET. These studies provide a means of estimating Kc as a function of some variable that is relatively easy to obtain, such as time or fractional cover.

7.5.2 Estimation of Kc and ET with Remote Sensors

As mentioned previously, the measurement of real ET is difficult and requires expensive equipment and specially trained personnel, irrespective of the chosen measurement method: lysimeters, soil humidity balance, eddy covariance, etc. Moreover, the crop factors obtained from these studies cannot be applied universally, since crop development is not the same in different years or in different places (even using the same irrigation scheme), nor are management practices in every field. Therefore, we need to look for an alternative method to estimate Kc. The method should be easy and cheap to perform and provide near real-time estimates. Fortunately, the same factors that affect Kc also affect spectral vegetation indices, and many authors have investigated the relationship between them (Garatuza/Watts, 2005; Zwart et al., 2006; Jayanthi et al., 2007; Rodriguez et al., 2009; and many others).

The hydrometeorology group at ITSON and UNISON have been using eddy covariance techniques to measure real ET since 1994 (Garatuza et al., 1998) for crops and natural vegetation, using measurement protocols described in Scott et al. (2003) and Perez-Ruiz et al. (2009). The group has recently collaborated with researchers from CESBIO (*Centre d'Etudes de la Biosphere*) in a field programme to measure real ET for many crops in order to determine Kc and relate these to other variables such as the spectral vegetation indices obtained from satellite data. These studies were mainly carried out in the Yaqui valley and Costa de Hermosillo in Sonora. In the next section results are presented for the most important crops in the region.

7.5.3 Costa de Hermosillo

Measurements of real ET were performed using two EC systems during 2005–2006 for two grape varieties (Perlette and Superior) and pecan. Climate data were obtained from the network of *automatic weather stations* (AWS) operated by INIFAP, and ET_0 for each measurement site was obtained using average values for the climate parameters from the closest AWS, where each value was weighted by the inverse of the squared distance. All available LANDSAT images for this period were collected (a total of 17) and NDVI values were extracted corresponding to the EC measurement sites. The ratio of measured ET over ET_0 (measured Kc) was obtained for the day of the satellite overpass and compared to NDVI from LANDSAT (figure 7.3). Linear regression gives

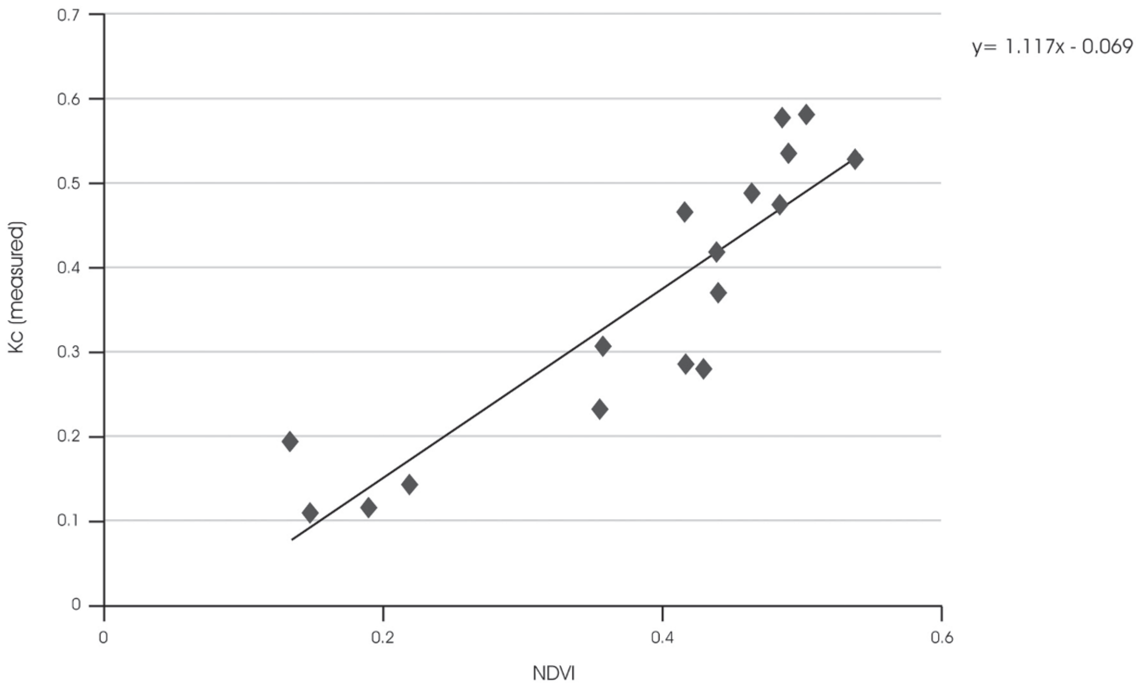
$$\frac{ET}{ET_0} = 1.117\,NDVI - 0.069 \qquad (r^2 = 0.8)$$

so that the slope is close to one and the intercept is close to zero. If the regression line is forced through the origin, we obtain a slope of 0.953 (r^2 = 0.782).

7.5.4 Yaqui Valley

During 2008 a large field campaign was conducted as part of the Pleiades project, to measure real ET using EC systems for seven different crops: broccoli, beans, chickpeas, chili peppers, potatoes, safflower and wheat. Crop development and management practices were carefully monitored and stored in a database. Satellite data were downloaded from the appropriate

Figure 7.3: Relation between Kc and NDVI for grapes in the Costa de Hermosillo during 2005 and 2006. The values of Kc were obtained using EC measurements of ET and ETo from local climate data. **Source:** Data elaborated by the authors based on NDVI obtained from Landsat 5 images.



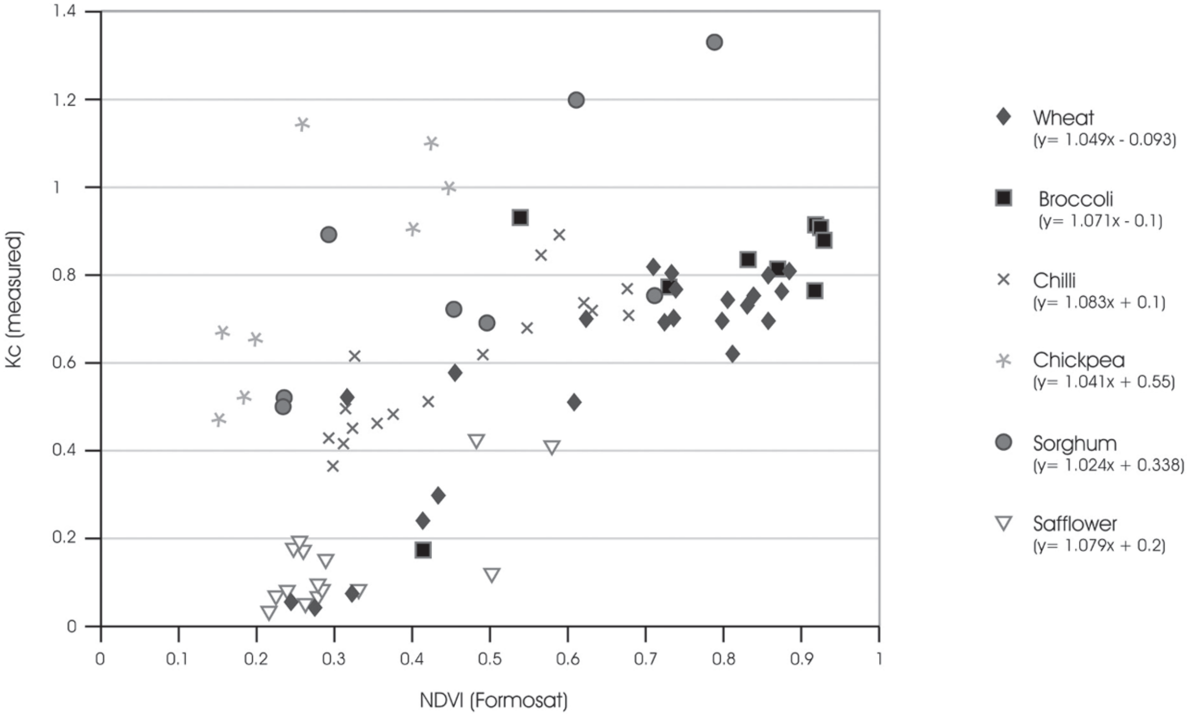
websites for Landsat, MODIS and GOES. The French Space Agency CNES (*Centre National d'Etudes Spatiales*) provided 40 images from the FORMOSAT satellite (8 metre spatial resolution) and NDVI values were extracted from these for each EC measurement site. ET_0 was calculated from data using the closest AWS (Block 1418) and Kc was calculated as the ratio of measured ET over ET_0. Figure 7.4 presents the results of relating measured Kc to NDVI. The slope and intercept for the linear regression line is shown for each crop. In each case, a line with slope equal to 1 provides a good approximation to the observed data, although not always the best one.

7.5.5 Spatial Distribution of Variables

In general, the measured values of ET and other meteorological parameters are representative of only a small area around the instrumented site. In contrast, the satellite images provide data for a large area around the site, so that they can be used to extrapolate the calibrated results at the measurement sites. The linear relationship expressing Kc as a function of NDVI can be used with GIS map algebra to obtain maps of Kc. Similarly, if a map of ET_0 is generated by interpolation between the values for each AWS in the area, then we can obtain a map of real ET as well. Figure 7.5 shows results for part of the Yaqui valley irrigation area for three days during the wheat-growing cycle in 2008. Only values for areas planted with wheat are shown and other crops have been masked out. The first column corresponds to 3 January at the beginning of the growing season, when the value is low (even zero in some places). The second column corresponds to 23 February when wheat is fully developed in the whole area, and the third column corresponds to 27 April in the final stage of the growing season, when most of the crop has become senescent. Note the distinctive 'stain' in the upper left of the images. In this zone, some external factors had prevented the crop from developing normally as in the rest of the area.

In the first row, NDVI maps obtained from Formosat are shown for the three dates. The values of NDVI are between 0 and 1, increasing with the amount of biomass on the surface. The second row shows maps of Kc, and the third row contains maps of actual ET (in mm d^{-1}) for the same dates. In the second column (23 February) Kc and ET have their highest values, with Kc around 1 and ET about 5-7 mm d^{-1}, corresponding to fully developed crops. By the third date (27 April) the vegetation is almost dry, while other areas, with later sowing dates or varieties with longer growing seasons, are still active. So both

Figure 7.4: Relationship between Kc and NDVI for six different crops in the Yaqui valley in 2008. Kc values were obtained from the ratio of measured ET (using EC systems) and ET_0. NDVI was obtained from Formosat images. The slope and intercept from linear regression are included for each crop. **Source:** Elaborated by the authors.



Kc and ET show a wide variation: 0.2–0.8 and 2–7 mm d^{-1} respectively.

7.6 Conclusions

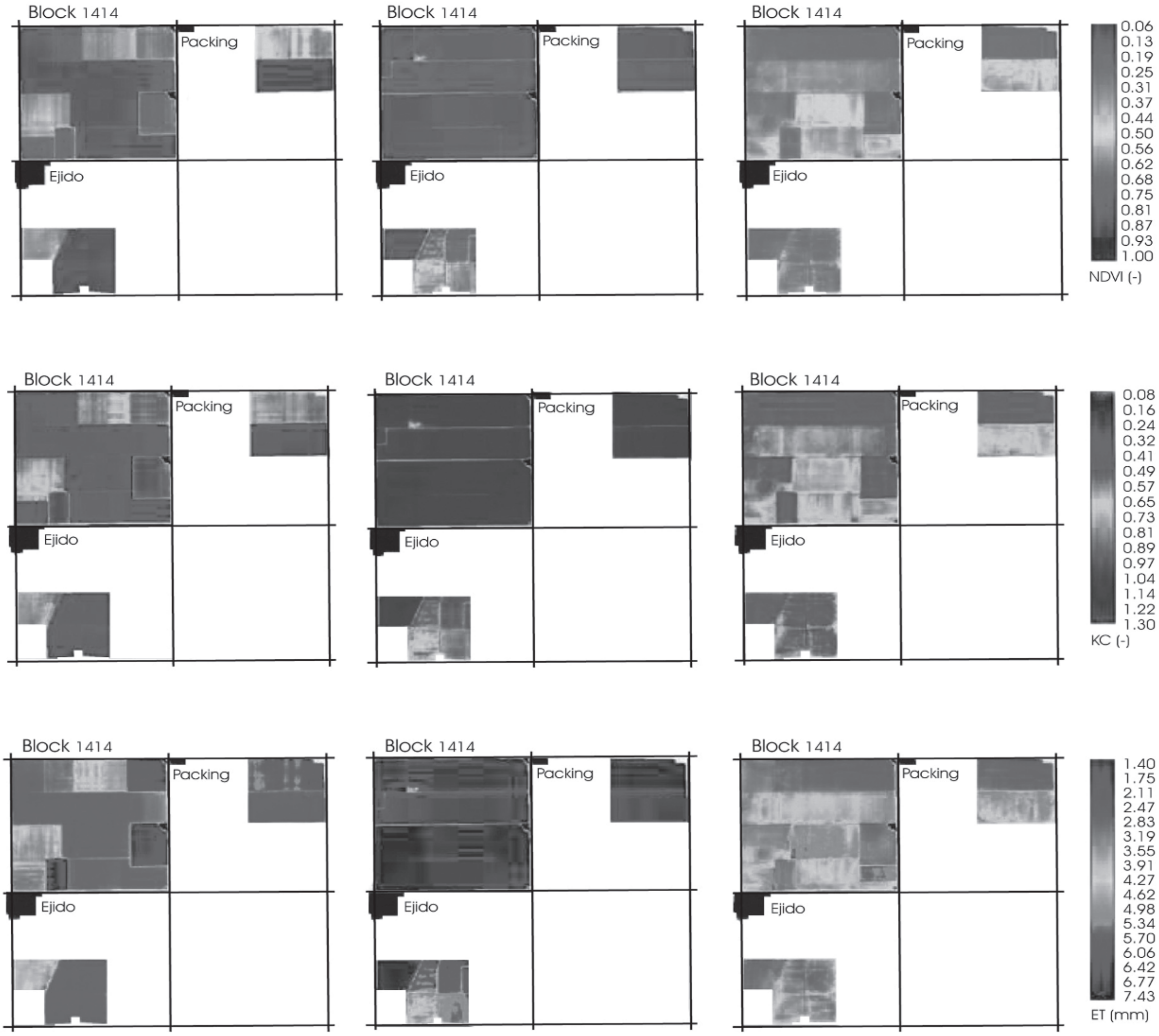
The estimation of water demand and use by crops is an important factor in the planning and operation of irrigation systems and also in hydrological studies to determine water availability in a region. Reliable methods to determine these are costly and complicated, so that it is common practice to use simple models instead, the most common of which is the two-stage model proposed by FAO. In this model, first the reference evapotranspiration (ET_0) is calculated using climate data collected from meteorological monitoring networks, and then the crop factor is determined.

The influences on crop factors are the same as those that affect spectral vegetation indices, generally based on the differences in the reflectance of the vegetation and soil in the red and near infrared bands of electromagnetic radiation. Therefore, it is possible to establish functional relationships between *vegetation indices* (VI) and *crop factors* (Kc), so that the latter may be estimated using routine observations from earth observation satellites.

The results of many studies carried out by the authors suggest that Kc can be represented as a linear function of VI with slope close to unity. The intercept is variable and depends on crop type and percentage cover.

These results indicate that a family of linear equations with unit slope and variable intercept (function of crop type and cover) could be used to provide near real-time estimates of Kc and ET with the necessary spatial and temporal resolution to be used operationally in irrigation scheduling. In order to accomplish this, it is essential that the climate data and remotely sensed data (from satellite, aircraft or other platforms) be available on time and the results be available online, so that the end users receive the information in a timely fashion. It is also important to maintain an up-to-date database with information on crop types, sowing dates, application of irrigation, fertilizer, etc.

Figure 7.5: NDVI (row1), Kc (row2) and actual ET (row 3) for three dates during the growing season for wheat in the Yaqui valley. Only values for the fields with wheat are shown; the others are blank. The three dates chosen are: 3 January (Column 1), 23 February (Column 2) and 23 April (Column 3). **Source:** Elaborated by the authors.



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8 Advances in Geomatics and Geospatial Technology for Solving the Water Problem in Mexico

Felipe Omar Tapia Silva

8.1 Introduction[1]

The problem of water is complex, and the occurrence of hydrological cycle variables and the other factors involved have an observable geographic reference and spatial and temporal variability. Based on this territorial perspective, studies aimed at solving the problem must consider a systemic approach, and this requires information and knowledge that reflect the spatial and temporal nature of such variables and factors.

Geomatics is a scientific discipline that has emerged from the convergence of earlier disciplines such as geographical information systems, spatial analysis, cartography, remote sensing, geodesy and photogrammetry. In general terms, it involves a series of methods for the acquisition, processing, representation, analysis and systematization of information and knowledge with geographic references (specific localization and spatial surroundings). The discipline sees society as the principal beneficiary of its studies and development projects; it includes society in its models of knowledge for the functioning of a territory by identifying the factors that influence both natural and human-induced changes. The systemic approach and the generation of information from remote sensors and geospatial models increase the possibilities for analysing and communicating how the processes that occur in a territory function, and for decision making. This scientific discipline is assisted by geospatial technology, that is, the use of technology to visualize, measure and analyse phenomena that occur on the land's surface and its immediate underlying layers.

This article presents the relevant tools (methods, information and knowledge) provided by geomatics and geospatial technology (which is included in geomatics) to help solve the water problem. Each one is described in summary form and supported by bibliographic sources and internet links that can be consulted for more detailed information. Among the most notable is the use of products from the LANDSAT, SPOT and MODIS missions, and other more specialized ones such as SRTM, TRMM and GOES. Geospatial analysis and modelling techniques are also important tools with great potential for application in the area of water science. This chapter also briefly describes and refers to examples of these techniques, such as a model for defining surface hydrological connectivity of territories based on *Digital Elevation Model* (DEM) analysis. Also mentioned are the design, implementation and utilization of the artefacts of geomatics developed in the area of water science, including the *Geographical Information System* (GIS) for the Mexico Hydrographic Basin, the Cybercartographic Atlas of Chapala Lake and the System for the Management of Urban Ravines in Mexico City. Remote sensing techniques for studying and monitoring hydrological variables are also highlighted and described with respect to their usefulness in water-related issues.

More than one billion people worldwide do not have access to clean water, and 2.6 million have no sanitary services (UNDP, 2006). The combination of various social, environmental and socio-economic pressures often results in increased use of and competition for water and in its contamination, as well as in inefficient water supply practices (UN-WWAP, 2006). The use of biophysical and socio-economic indicators that combine measurable data relevant to public policies provides the basis for diagnosing the current status of the problem and for decision-making (MA 2005, chapter 1). Unfortunately, in the context of probable climate change, it will be substantially more difficult to quantify the range of possible modifications in the hydrological cycle than in the context of global mean temperature (Allen/Ingram 2002). Natu-

1 Keywords: spatial analysis, remote sensing, cyber-cartographic artefacts, systemic approach, territorial perspective

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ral and socio-economic factors that characterize, influence and interact in the problem of water comprise a series of processes that are difficult to understand, even with the most comprehensive perspective possible.

The water cycle and water usage are phenomena that are intrinsically associated with space. Hydrology is therefore defined as a geographic science. The components of the cycle, and other factors involved in the complex problem of water, have an observable geographic reference and spatial and temporal variability. From a territorial perspective, studies aimed at influencing the solution must consider a systemic approach, and they require information and knowledge that reflect the spatial and temporal variability of the factors involved. In the context of a territorial approach, a systemic perspective must have the characteristic of identifying the elements that comprise the hydrological system in question (a basin or catchment area or a specific territory defined by other types of criteria, for example, the political), and analysing the relations and dynamics of change that are observable among these elements.

8.2 Objective and Methodology

8.2.1 Objective

There are an enormous number of investigations that study water issues based on the disciplines included in geomatics. Hence, this chapter gathers together a sample (not exhaustive) of studies so that the capacities of this science and its convergent disciplines can be appreciated; the aim is to support the study of the variables of the hydrological cycle based on a territorial analysis of the water problem so that initiatives and public policies that help solve the problem may be generated.

8.2.2 Methodology

The first section is a primarily conceptual perspective on the possibilities of geomatics (its systemic approach, remote sensing techniques and spatial analysis) for the study of complex water issues. Next, a summary of the water problem in Mexico is presented, followed by a section that highlights the application of research results, with a review of the methods, information and knowledge that geomatics and geospatial technology (primarily remote sensors) provide for the solution of the problem described in the previous section. Methods discussed include the use of remote sensing products from the LANDSAT and MODIS (*Moderate Resolution Imaging Spectroradiometer*) missions, and other more specialized products such as SRTM (*Shuttle Radar Topographic Mission*) and TRMM (*Tropical Rainfall Measurement Mission*). Also mentioned are geospatial analysis and modelling techniques that have great potential for application in the study of water issues, including the model for defining a territory's hydrological surface connectivity based on *Digital Elevation Model* (DEM) analysis, as proposed by Jenson and Domingue (1988). The integration of GIS information is also discussed in this section. The last section describes cybercartography and its possibilities in the area of water science. Included are descriptions of geomatic artefacts developed in Mexico, such as the Geographical Information System for Mexico's Hydrographic Basins, the Cybercartographic Atlas of Lake Chapala and the System for the Management of Urban Ravines in Mexico City. General conclusions are then presented.

8.3 Results

The results of the review as well as the ideas for developing the issues mentioned in the methodology section are presented in the order in which they appear above.

8.3.1 Geomatics for Studying the Complexity of Water Issues

Since it is difficult to define a complex system (Bourgine/Johnson, 2006*)*, the reference quoted only observes that a region's hydrological problem fulfils the primary characteristics of a complex system. This includes evolution and adaptation due to external and internal interactions (such as climate, population and economic pressures), and possible changes in the boundaries of a system and the links between a system and its surroundings (for example, the case of Mexico City, where alternative supply sources from other regions continue to be sought). We observe that the hydrological cycle is composed of a set of physical elements or processes (the components of the hydrological cycle) that are joined together interdependently. The cycle has input and output variables from the perspective of balance in a particular geographic zone or territorial unit (a block, neighbourhood, city, state, country, a rainwater catchment area, or a river basin).

Precipitation is the best known and most important hydrological input variable, observed as water in the form of rain, sleet or falling snow. This hydrological variable shows a large degree of spatial and temporal variability, as do the others. Thus, on specific days and places, different amounts of precipitation are observed. Important output variables are surface run-off and evaporation. Complex relations between hydrological variables (which can be considered as subsystems) are observed – for example, in the study of evaporation. This variable depends in a complex way on the behaviour of other hydrological variables (for example, the amount of precipitated water and the amount that manages to infiltrate) and on complicated interrelations with other factors (such as climate). In addition, the accelerated process of change in land use is a factor that directly affects infiltration, run-off and evaporation variables.

The attempt to capture the spatial and temporal variability of precipitation has traditionally been made through point measurements. These measurements are used to generate climatic reports to provide information for recording moderate, strong or extreme precipitation. Geomatic techniques serve an important function, beginning with the acquisition and processing of such climate information. Since the records obtained using measurement stations have spatial and temporal references, they are valuable and useful for knowing, with certainty, the time and space in which the phenomena of interest have occurred.

However, it is commonly assumed that point measurements of precipitation and other climatic parameters are valid only within a radius of a few kilometres, as indicated by Daly (2006) for mountain areas. And since measurement stations are separated by tens, if not hundreds, of kilometres, this presents a problem for spatial representativeness in the generation of surfaces based on point measurements. Geomatics provides a series of interpolation methods for such a purpose. This type of geostatical method is described by Goovaerts (1997), for example. Auxiliary variables, such as terrain heights normally represented by *Digital Elevation Models* (DEMs), are commonly used in interpolation processes for point measurements of precipitation, for which Goovaerts (2000) proposes the Kriging with External Drift technique. This technique can be used to generate combined precipitation products between land radars and point measurements, as described by Goudenhoofdt and Delobbe (2008). Geomatics also provides more sophisticated techniques for measuring precipitation with remote sensors. International advanced missions, such as TRMM, estimate precipitation on a global level based on sensor packages: the first *space precipitation radar* (TPR), a *microwave sensor* (TMI) and a *visible ultraviolet scanner* (VIRS).

Kummerow et al. (1988) provide a detailed description of the sensors that make up TRMM, as well as a preliminary determination of its effectiveness. Estimates from this mission have facilitated climatic analysis studies and the management of water resources (Chiu et al. 2006). One of the results of TRMM is a database with 9 years of rainfall and cloud cover information, accessible to the public by downloading. This is a noteworthy source of information for the analysis of precipitation in tropical zones (Liu et al. 2008). In addition, techniques to improve the precision of these precipitation calculations, aided by satellite images, are being researched to generate precipitation maps that combine field and satellite measurements (Adler et al. 2000). Thus, geomatics has enabled a series of significant advances to occur in defining with a greater degree of precision the amount of water that precipitates over the territorial units of interest. Scientific disciplines included in geomatics (cartography and cybercartography as described in section 8.3.4) facilitate correct cartographical expression (maps and other types of spatial expressions) and a geographic and comprehensive analysis that considers cross-cutting socio-economic and natural factors.

What is observed after precipitation occurs depends on the spatial configuration (primarily the types of land use and ground cover) of the territorial unit being studied. If it is a highly permeable zone with little influence from human activity, a large part of the water will most likely infiltrate it (and some part of this would reach the aquifer springs) and another part would evaporate off the vegetation surfaces and ground layers. On the other hand, if the zone involved is highly urbanized and impermeabilized or deforested, greater quantities of run-off water are generated along natural beds (rivers and streams) or artificial ones (streets and highways), and this can unleash tragedies of great magnitude.

Between these two opposite situations is a wide variety of ground cover and other types of land that largely define the division of pluvial precipitation between infiltration and recharge of aquifer springs, run-off, and evaporation. Geomatics also plays a fundamental role in the study of these processes. The most rapid, certain, and economical way to define types of ground cover is through the interpretation of satellite images. Each type of ground cover has a different response (expressed as absorption, transmission and reflectance) to the incident light (usually solar light) registered by satellite images. LANDSAT satellites and other missions, such as SPOT, have frequently been used in Mexico to define ground cover precisely. Indeed, the use of LANDSAT could increase, since this mission's products have been available at no cost since the end of 2008 (<http://edcsns17.cr.usgs.gov/EarthExplorer/>). In one year, it is possible to have four or more LANDSAT images from the same region and a similar number of SPOT images. Consequently, it is feasible to follow the temporal ground cover changes very adequately. The spatial resolution of these images, that is, the minimal territory detected by a SPOT or LANDSAT image, varies between 15*15 and 30*30 m^2, and this enables sufficiently detailed studies to be conducted. In addition, there are spatial images with even greater spatial resolution (such as IKONOS with pixels of less than 1 m^2). MODIS is also a mission of great interest to the study of hydrological variables. This sensor registers information according to 36 spectral bands and, therefore, has more possibilities for monitoring biophysical variables than other sensors such as LANDSAT, although the spatial resolution of this sensor (250*250 m^2, 500*500 m^2 and 1000*1000 m^2, depending on the spectral band) is less than that of LANDSAT and of SPOT.

Techniques developed in the field of geomatics also enable the direction in which water runs to be assessed, once it has precipitated and where it is located on a surface with low permeability. This is accomplished using *Digital Elevation Models* (DEMs). In addition, this process allows the areas in which water accumulates to be detected. DEMs are likewise produced by techniques generated by the scientific disciplines that make up geomatics. A notable source for DEMs on a global level is NASA's *Shuttle Radar Topography Mission* (SRTM 2003). The available DEMs produced by this mission, with 90 m of spatial resolution, are also available for downloading from the internet at no cost (ftp://e0srp01u.ecs. nasa.gov). For special cases (available by request), it is possible to obtain 30-m DEMs, the spatial resolution at which the DEMs from this mission were originally produced based on radar signals. A model for defining hydrological surface connectivity that is widely known and used is that proposed by Jenson and Domingue (1988). The fundamental premise of this model is that water flows in the direction of the greatest slope. A first processing step for DEM is to remove artificial depths, known as fill sinks. In order to do this, interpolation is conducted before creating the raster map for flow direction. This is done because artificial depressions (not real but, rather, produced by errors in the generation of the DEM) can significantly alter the directions of flow. According to the system proposed by Jenson and Domingue (1998), there are at least eight cells that border each cell in a DEM and, therefore, flow in any one of those eight directions is possible. These are determined, by convention, as 2^x where x = {0,1,...7}. The calculation of flow directions is based on the definition of the steepest gradient from the centre of each cell towards the centre of its neighbouring cells. In the Jenson and Domingue (1998) model, the definition of flow accumulations is the next step for defining the hydrological surface connectivity system. The corresponding map is created from the directions of flow and registers the quantity of cells that flow towards one particular cell. The flow from one cell may not reach the exit point of the basin or collection area because of errors resulting from errors in the generation of the DEM or because the DEM scales are not sufficient to register the changes in slope and, therefore, the drainage lines. In this case, Maidment (2000) recommends applying the procedures for correcting such imprecision in the model, such as 'DEM burning', which results in an artificial 'elevation' of the watershed, or 'sinking' of the low or flow accumulation zones, so that flow towards these zones is assured.

Evaporation is another relevant hydrological variable. This variable is fundamental for studies based on hydrologic balance and water availability. Its determination is complex, and advances in geomatics provide elements for a more precise and diversified determination of this variable, such as methods that are available related to the use of biophysical variables obtained from remote sensors. Among the most well known are SEBAL (*Surface Energy Balance Algorithm for Land*, Bastiaanssen et al., 1998) and METRIC (*Mapping Evapotranspiration at high Resolution with Internalized Calibration,* Allen et al. 2007). Both methods are based on obtaining the evaporative term from the surface energy balance.

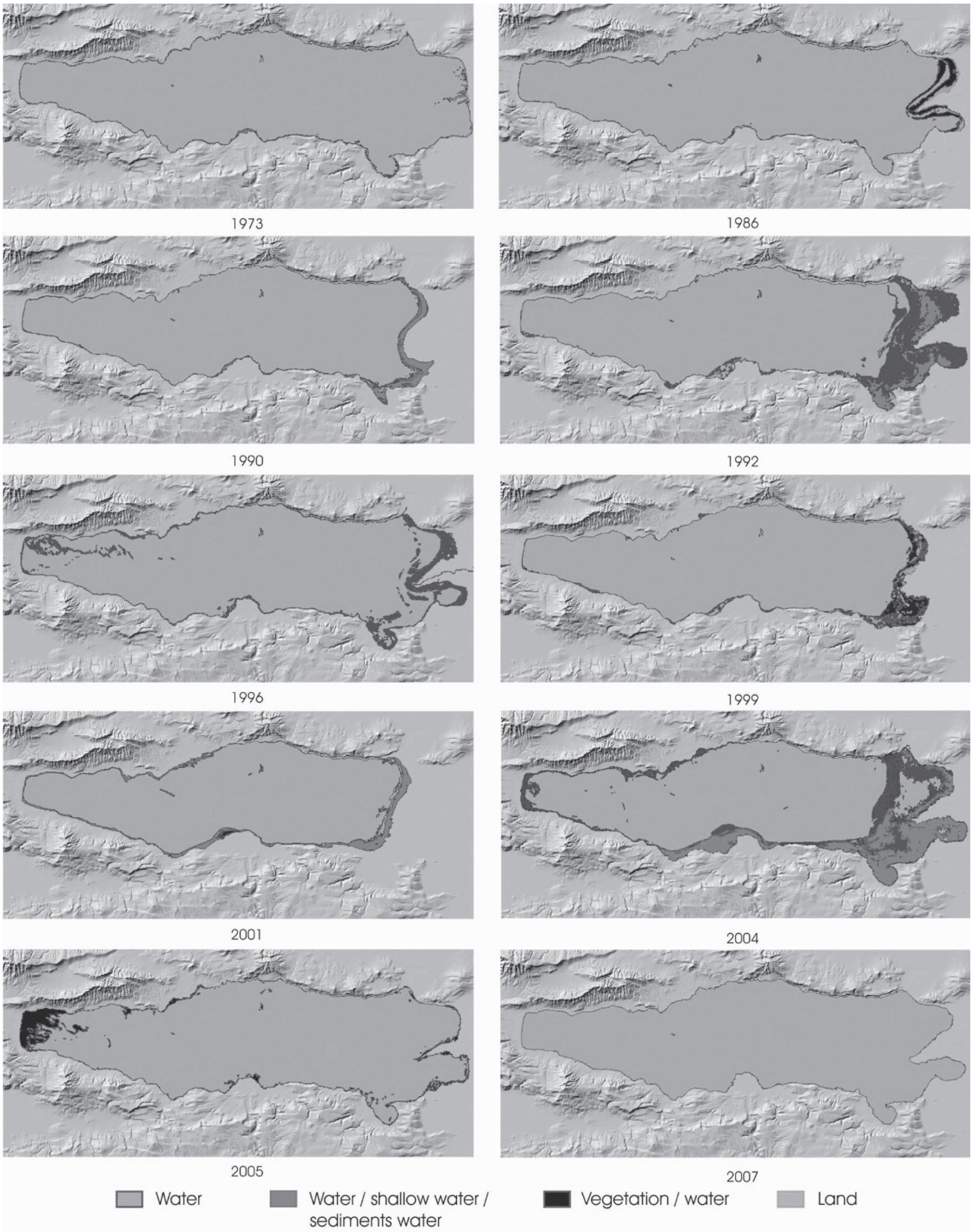
SSEB (Senay et al., 2007) is another example of this type of methodology. In general terms, this is a method based on remote sensing that enables obtaining a reduction function to obtain a real value for evaporation based on a reference or potential evapotranspiration value. In SSEB sets of hot and cold pixels are used to obtain this reduction function. Cold pixels are selected based on those with *low surface temperature* (LST) and a high vegetation index (NDVI), and hot pixels are selected according to the opposite criteria. Some of the biophysical variables required by these models (LST and NDVI) are available at no cost, for example, as satellite products such as MODIS. LST is a good indicator of surface energy balance and is therefore used to estimate evaporation. NDVI is an indicator of the density and health of existing vegetation and is also an important value for the calculation of evaporation using remote sensing. Applications of these models in Mexico are included in 8.3.3.

8.3.2 Summary of the Water Problem in Mexico

Water was initially considered to be a renewable natural resource (at least in the collective imagination of Mexico), but this is no longer the case. Another negative aspect is the emergence of problems generated by changes in precipitation patterns (which are not even predictable, according to Allen and Ingram, 2002) as a consequence of climate change. These changes are expressed by a greater incidence of extreme phenomena (droughts and intense rains) and by a destabilization in precipitation regimes (Easterling, 2000). In addition, complications exist as a result of the decrease in and contamination of aquifers and bodies of surface water (see below). These events indicate that in the context of poorly planned human intervention on the land, water cannot alone maintain itself as a vital resource for life and the development of human society and the ecosystem on which it exists. The following are some of the more significant cross-cutting hydrological problems observed on a national scale:

- Incidences of torrential rains and surface impermeabilization that create floods and landslides and impede aquifer recharge. With regard to hurricanes, CONAGUA (2007) observed that 47 hurricanes occurred between 1980 and 2006 and that between 2001 and 2006, phenomena of category 3 or higher have been more frequently recorded. With respect to impermeabilization, a good deal of research is lacking in order to discover the current extent of this process in our country, though the degree of impermeable surfaces has been determined for some cities, including Campeche, León and Mexicali; this was carried out by CentroGeo (2007), as mentioned in section 8.3.3.
- Drying up and contamination of aquifers (104 out of 653, see CONAGUA, 2007) due to over-exploitation and serious deficiencies in planned land use.
- Wasting rainwater and its contamination from becoming mixed with sewage. CONAGUA (2007) reported that 36 per cent of municipal water is treated; however, treatment levels of plants vary a great deal and treatment is usually performed at a primary level (CONAGUA, 2007).
- Contamination of surface water by residual waste contaminants. According to CONAGUA (2007), based on monitoring three quality parameters (biochemical oxygen demand, chemical oxygen demand and total suspended solids), between 8 and 30 per cent of total surface run-off is contaminated.
- Increase in river flows produced by deforestation and a decrease in water above the basins as a result of poorly planned usage. Investigation is needed to precisely define the current situation. Only preliminary results are available, such as the study conducted by Tapia Silva et al. (2007a; figure 8.3) of deforestation in the south-eastern basins and its relation with increased run-off, as well as that by Preciado et al. (2004) of the Quelite basin on the Guatemala border.
- Poor efficiency in the use of water in agricultural and urban zones. CONAGUA (2007) reported a total use for agricultural purposes of roughly 80 per cent of the national total, which suggests the need to improve the efficiency of irrigation through water-saving technologies. Nevertheless, CONAGUA (2007) also reported increased productivity in the use of water (quotient between total crops and total applied irrigation volume, expressing the amount of kg of crops obtained per m^3 of water) of 1.11 during the 1995–1995 agricultural cycle and 1.41 between 2004 and 2005.
- Reduction and disappearance of water bodies as a result of negative balances between inputs (from precipitation and surface and subterranean water flows) and outputs (caused by evaporation and anthropogenic uses). Studies to define the current general situation for this issue are also lacking. Those that exist deal with specific bodies of water, such as that conducted of Chapala Lake (López Caloca et al., 2008; figure 8.1). Section 8.3.3 presents a sequence for that area from 1973 to 2007, describing how geomatics and geospatial technology can contribute to solving this problematic situation, and gives examples of some of the related investigations.

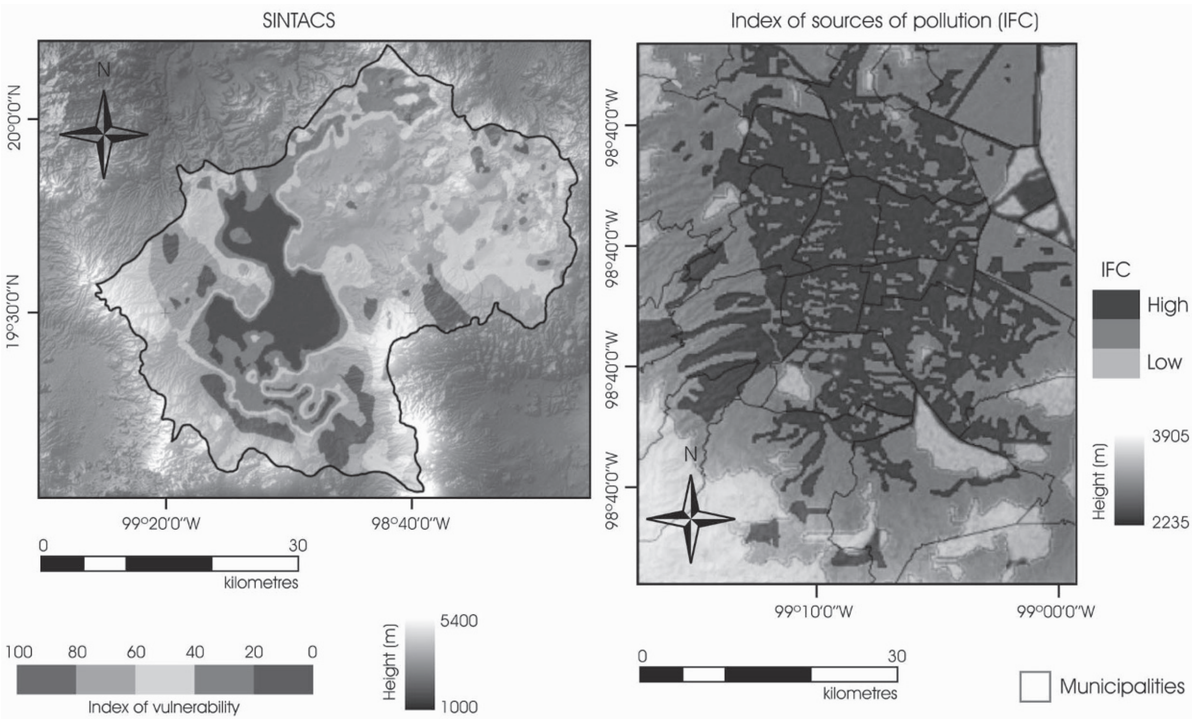
Figure 8.1: Changes in the area of Chapala Lake, monitored by LANDSAT and SPOT. **Source:** López Caloca et al. (2008).



8.3.3 Examples of the Application of Geomatics and Remote Sensors to Solving the Water Problem

The studies included here (most of which were conducted on a regional or local scale in Mexico) indicate how geomatics and the disciplines it encompasses facilitate the generation of information and knowledge for creating projects and tools for public policies that will contribute to solving the complex water problem summarized above. The information and knowledge acquired can support decision making to

Figure 8.2: Left: Aquifer vulnerability to contamination in the Mexico Valley Basin. Right: index of sources of contamination for the Mexico City urban sprawl zone. **Source:** Ramos Leal et al. (2010).



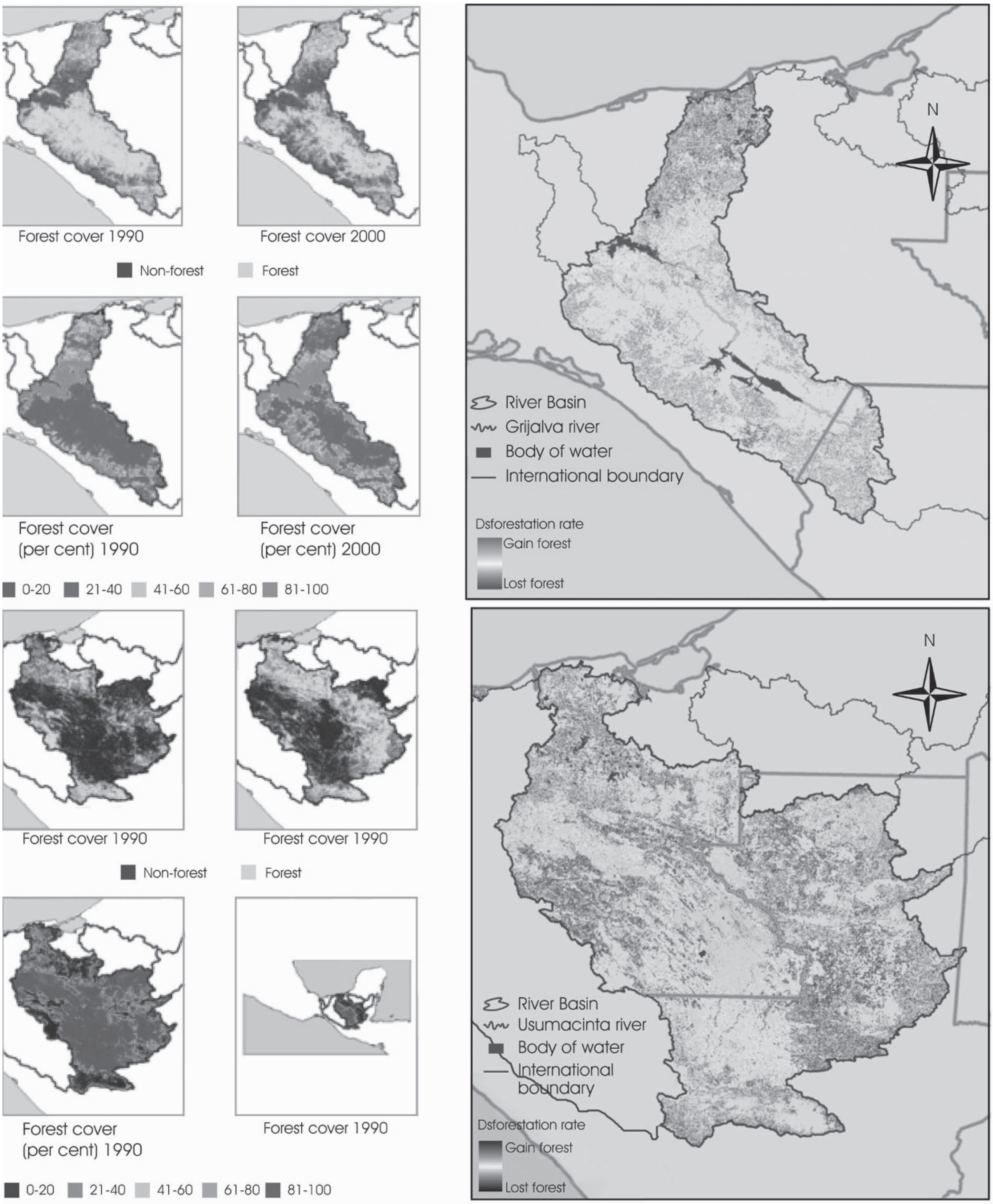
improve the management and conservation of this valuable resource. Based on GIS, these studies integrate geospatial information from various sources (including remote sensing). Other geomatic disciplines, such as cartography, spatial analysis and cybercartography (see 8.3.4) provide elements for generating and communicating information and knowledge about the water issue.

In geomatics, it is possible to conduct studies about the sealing of permeable surfaces and those that are capable of aquifer recharge (Tapia Silva/Mora, 2004). With regard to impermeable surfaces, it is possible to create methodologies using SPOT-5 images to study precarious settlements, such as that performed by CentroGeo (2007) for the Secretary of Social Development in Mexico. This methodology includes the application of the VIS (*vegetation-impervious surface-soil*; Ridd, 1995) model. This is an empirical model that relates ground cover data obtained with remote sensing to the biophysical aspects of urban environments within a hierarchical decision-making strategy. Another option in geomatics is monitoring changes in the areas of lakes and relating them to trends in hydrological and climatic variables, as well as to others such as water extraction and availability from bodies of surface water. One example is the Chapala Lake study conducted by López Caloca et al. (2008), which presents a temporal sequence showing changes in the area of Chapala Lake, monitored by LANDSAT and SPOT (figure 8.1).

This study and that by Lira (2006) apply segmentation methods based on the interpolation of water indices such as NDWI (*Normalized Difference Water Index)*. Lira (2006) defines lakes such as Patzcuaro, the Centla marsh, and lakes in Mexico City. It is also possible to propose the location of well recharge restoration points for aquifers or collection points for rainwater or surface water, as did Saraf et al. (2004). Another very recent application of geomatic techniques is for defining zones prone to flash flooding. One example of this type of study is that performed by Tapia Silva et al. (2007b) for the urban ravines zone in Mexico City. It is even possible to generate real-time maps of flood zones that allow for the planning of immediate responses to disasters, as reported by Matgen et al. (2007). Another example is the flood maps of Tabasco published by UNOSAT (2007) which, on 7 November 2007, provided information that was fundamental to responding to the disaster that began one week before and ended in the last days of November. In this case, the sensors used were MODIS and SRTM.

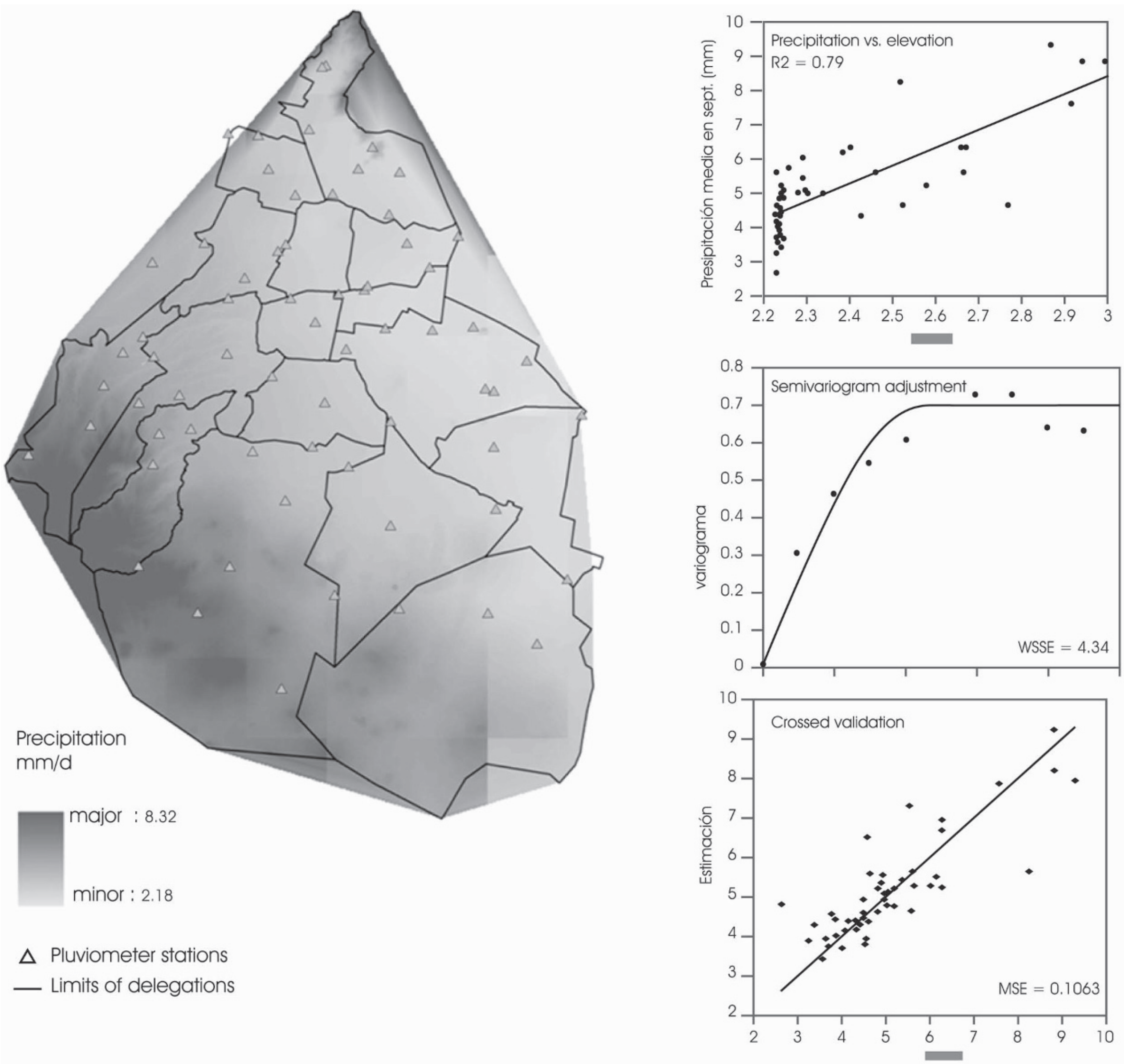
With regard to assuring organized land use from a hydrological perspective, geomatics makes it possible

Figure 8.3: Deforestation rate between 1990 and 2000 for large hydrological basins in south-east Mexico, obtained from LANDSAT images. Left: Grijalva; Right: Usumacinta. **Source:** Tapia Silva et al. (2007a).



to identify the zones with the best capacity for aquifer recharge that should be maintained intact, or not be urbanized or occupied for habitation purposes, since they can represent serious dangers from run-off accumulation. An example of this is the study by Tapia Silva and Arauz (2007a). Likewise, it is possible to determine the spatial variability of the vulnerability of an aquifer to contamination and the location of

Figure 8.4: Spatial variability of multi-annual precipitation for September in Mexico City, resulting from Kriging with External Drift interpolation, using the linear dependency between the digital elevation model and precipitation values. **Source:** Designed by the author based on research data.

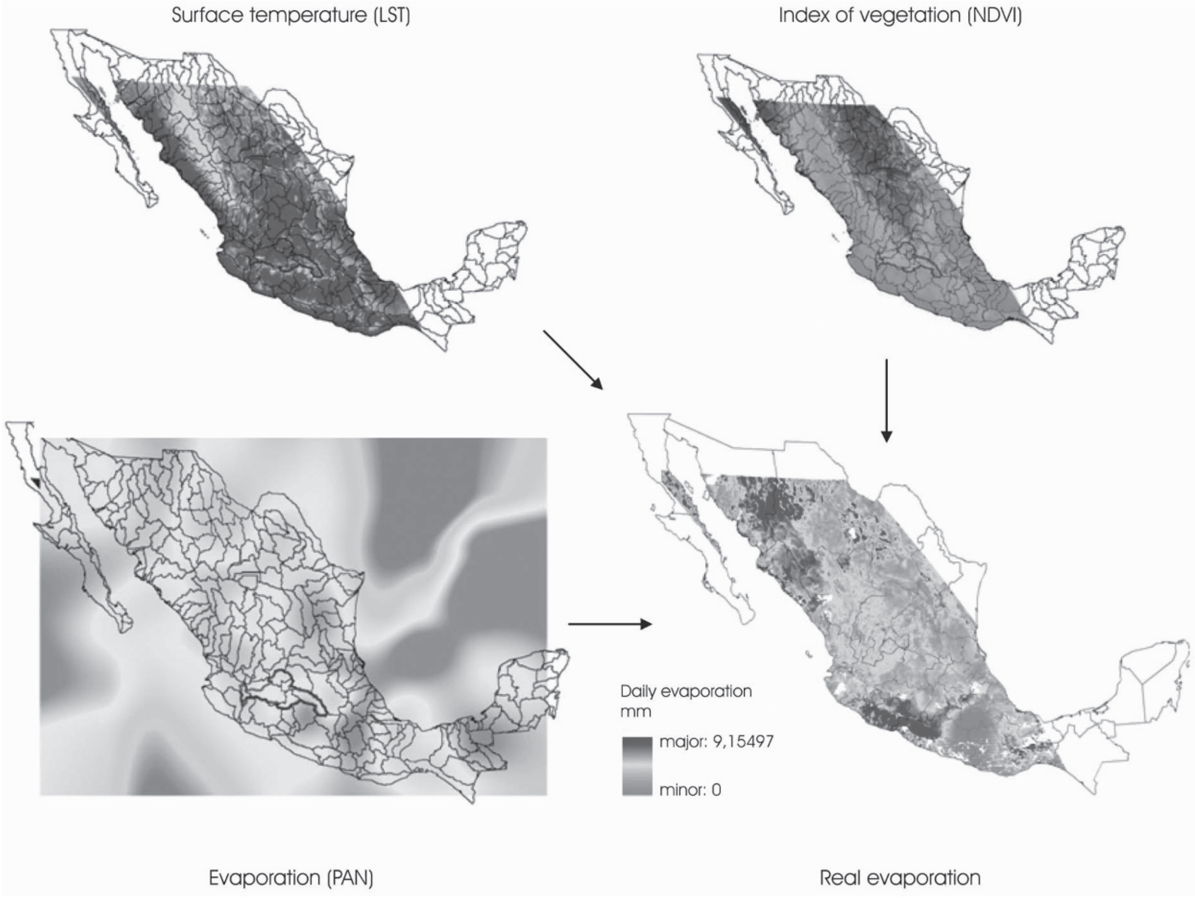


sources (geographic points or zones) of contamination of bodies of surface or subterranean water. This was conducted for Mexico City and its metropolitan zone by Ramos Leal et al. (2010). Figure 8.2 shows images from this study, indicating the zones that are prone to contamination and an index of sources of contamination.

Studies on the availability of resources by hydrogeologic basins are also greatly valuable. For example, Ramos Leal and Hernández Moreno (2008) conducted a series of reflections on the usefulness of a regional approach to the study and management of hydrogeologic basins in San Luis Potosí and the Mexico Valley. It is also possible to determine the influence of deforestation on increased run-off, as illustrated by Benitez et al. (2004). Figure 8.3 includes images from Tapia Silva et al. (2007a) for the Grijalva and Usumacinta basins (south-east Mexico and Guatemala), showing deforestation rates calculated between 1990 and 2000 based on LANDSAT images. A similar study was conducted by Preciado et al. (2004) for the Quelite basin on the Guatemala border.

The generation of cartography for spatial and temporal hydrologic and climatic variables is also possible in geomatics. Gochis et al. (2007) present an analysis of the spatial and temporal characteristics of the

Figure 8.5: Calculation of real evaporation in Mexico according to SSEB (Senay et al., 2007) for the winter of 2002, calculated using MODIS products and PAN evaporation measurements. **Source:** Coronel et al. (2008).



intensity of precipitation in north-east Mexico for the period 2002 to 2004. Golicher et al. (2004) use Universal Kriging to define precipitation and temperature patterns related to the 'el Niño' phenomenon on the southern border. Figure 8.4 presents results from an interpolation procedure for multi-annual daily precipitation for September in Mexico City. The method used Kriging with External Drift, taking into account the linear dependency between precipitation and elevation values.

The study of zones with low indices for efficient water use and the generation of proposals to increase these indices is another viable activity. Mo et al. (2005) use geographic land use layers, DEM, soil textures and an index for leaf area index taken from AVHRR (*Advanced Very High Resolution Radiometer*), in addition to interpolated climatic data to calculate crops, water consumption and an index for the efficient use of water. Aquifer studies as hydrologic balance and consumption of groundwater resources are supported by studies to calculate evaporation using PR (Bastiaanssen et al., 2005). For example, Zwart et al. (2006) used SEBAL to calculate water productivity for wheat crops in the Yaqui Valley in Sonora, Mexico. Garatuza Payan et al. (2001) used GOES *(Geostationary Operational Environmental Satellites*) images to obtain radiation values and then used those to calculate evapotranspiration according to Makkink's formula. Values derived from the satellite images were roughly 9 per cent less than those from field measurements. In addition to the above, Garatuza Payan et al. (2005) calculated crop coefficients as a function of vegetation indices (NDVI and SAVI: *Soil Adjusted Vegetation Index*), based on which they derived real evapotranspiration using reference evapotranspiration. Scott et al. (2003) validated the use of SEBAL for the calculation of soil moisture in an agricultural zone in Cortazar Guanajuato and analysed their results in the context of resource management. With regard to desertification, Lira (2004) proposed a model based on TSAVI (*Transformed Soil-Adjusted Vegetation Index*) and applied it to a portion of a LANDSAT image from 1996 in the northern zone of the country. Coronel et al. (2008) calculated real evaporation for the Mexican territory using SEBAL (Bastiaanssen et al., 1998) and SSEB (Senay et al., 2007) methods, in addition to data from MODIS products and PAN evaporation measurements (figure 8.5).

8.3.4 Cybercartography and its Possibilities for Water-related Problems

Cybercartography, through its practical expression in geomatic artefacts, can influence the solution to the complex and problematic water situation. It is worth noting that a substantial part of the theoretical advances in this discipline and many of its applications have occurred in Mexico at CentroGeo. Another relevant aspect is that the information and knowledge from studies such as those reviewed in the previous section can be integrated and structured as artefacts so as to maximize their usefulness to decision-making processes.

According to Taylor (1997) at the *International Cartography Association* (ICA) in Stockholm, cybercartography "transforms socio-economic, scientific and environmental data into interactive representations that allow the user to explore and understand spatial patterns and relationships in new ways". Reyes (2005) proposed the first theoretical conceptual framework for cybercartography, which establishes cybernetics, modelling and systems theory as the pillars of this new science. This approach represents an observed situation in terms of a conceptual model that comprehensively describes its generic structure using a systemic focus in order to facilitate the representation of the observed situation as diverse structural levels and the selection of the elements or agents involved (Reyes, 2005). Reyes (2005: 78) states that geospatial information is expressed using different languages, such as "maps, graphics, images, diagrams, videos, photographs, text, sounds and music (and potentially via touch and smell)", that should be "designed, in-tegrated and presented in such a way that the user receives the geospatial information". A fundamental aspect of the definitions provided by Reyes (2005) is the incorporation of the development of geomatics into social and organizational processes so that it becomes dynamic, or 'vivid', in the sense that "it can evolves according to the users' wishes" (Reyes et al., 2006: 12).

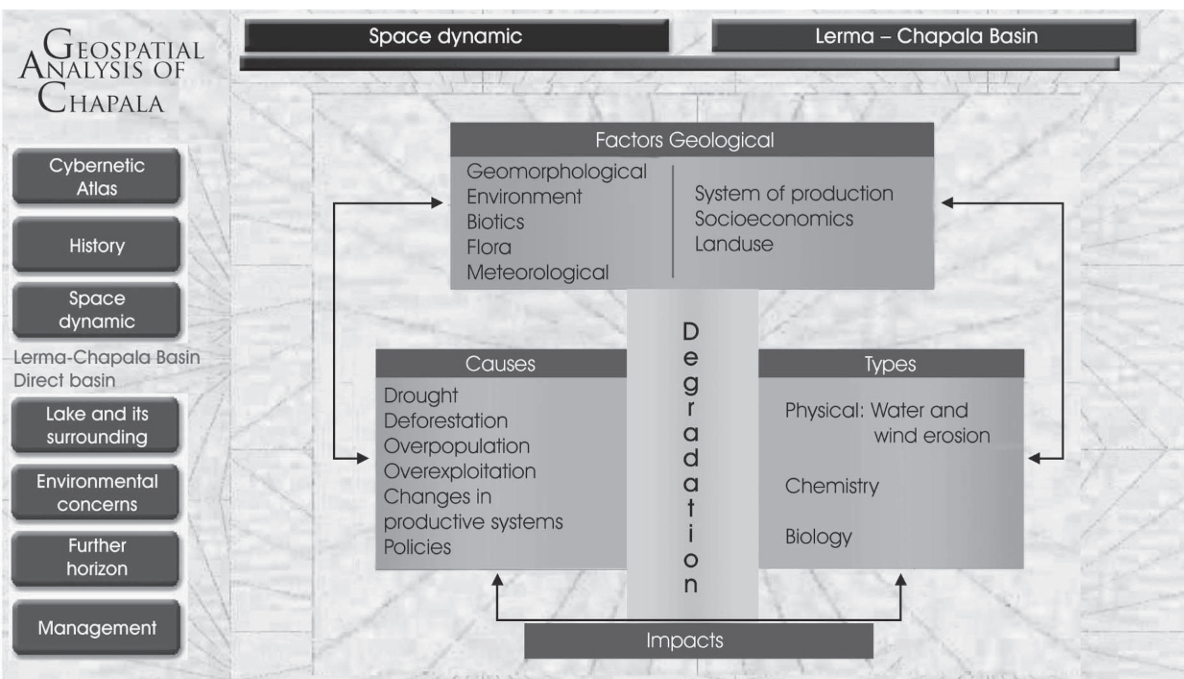
Geomatic artefacts (for personal computers or in their web version) may be geomatics' most significant contribution to the solution of cross-cutting hydrological problems with other types of societal concerns. Geomatic artefacts refer to cybernetic developments, prototypes and applications that provide feedback to geospatial knowledge and information – for example, atlases, documents, systems and solutions in geomatics. Their development combines a series of elements that make possible bidirectional communication processes with users who, in turn, access the elements that enable them to observe themselves as actors within each application's specific environment. This process is called second-order cybernetics (Martínez/Reyes, 2005).

Thus, it has been observed that while using geomatic artefacts, a process occurs that modifies the perspective of the user of the artefact. The users then propose improvements to the artefacts that permit them to re-access another series of concepts, information and ideas; and thus the perspective towards the problematic object of the artefact, and its solution, continue to evolve. An important characteristic of geomatic artefacts is their comprehensive and systemic perspective regarding the problems, or phenomena, that they represent. One of the principal components of this perspective is the requirement to observe and represent the phenomenon in question while taking socio-economic and technical-natural aspects or characteristics into account. Thus, the problem to be addressed in the environment of the artefact is comprehensively observed and analysed, maximizing the possibilities of identifying solutions that may be socio-economic, technical, biophysical, or a combination of these. The systemic approach and the inclusion of knowledge models allow the complexity of the hydrological problem to be represented.

Since its founding approximately 10 years ago, CentroGeo has developed a series of geomatic artefacts for the purpose of organizing knowledge and information that facilitate initiatives to solve cross-cutting hydrological problems. The applications developed, framed theoretically in the context of cybercartography, exemplify the possibilities and reaches of the practice and science of geomatics for solving specific societal problems. Included among such artefacts are the Geographic Information Systems of the Hydrographic Basins of Mexico (figures 8.6 and 8.7), the Cybercartographic Atlas of Chapala Lake (figure 8.8), the Educational Atlas of Chapala Lake, the Cybercartographic Atlas of the Lacandona Forest, the Cybercartographic Atlas of Lake Pátzcuaro, the Cybercartographic Atlas of the Sea of Cortes and an application for the Management of Ur-

Figure 8.6: Principal screen of a geomatic artefact on the web (under development). **Source**: Mexican Geographic Information System of Water Basins; at: <http://xsei.centrogeo.org.mx/ine/>.

Figure 8.7: Screen for the Cybercartographic Atlas of Chapala Lake. **Source**: http://mapas.centrogeo.org.mx/website/chapala/chapdegradacion/viewer.htm.



ban Ravines in Mexico City (SGBUCM, Tapia Silva et al., 2007c; figure 8.8).

As mentioned, geomatic artefacts are based on explicit knowledge models for the specific phenomena they represent. This facilitates the definition of future

Figure 8.8: Example of screens for the application of geomatics in the Cybercartographic Atlas of Chapala Lake. **Source:** Cybercartographic Atlas of Chapala Lake; at: <http://mapas.centrogeo.org.mx/website/chapala/chapdegradacion/viewer.htm>.

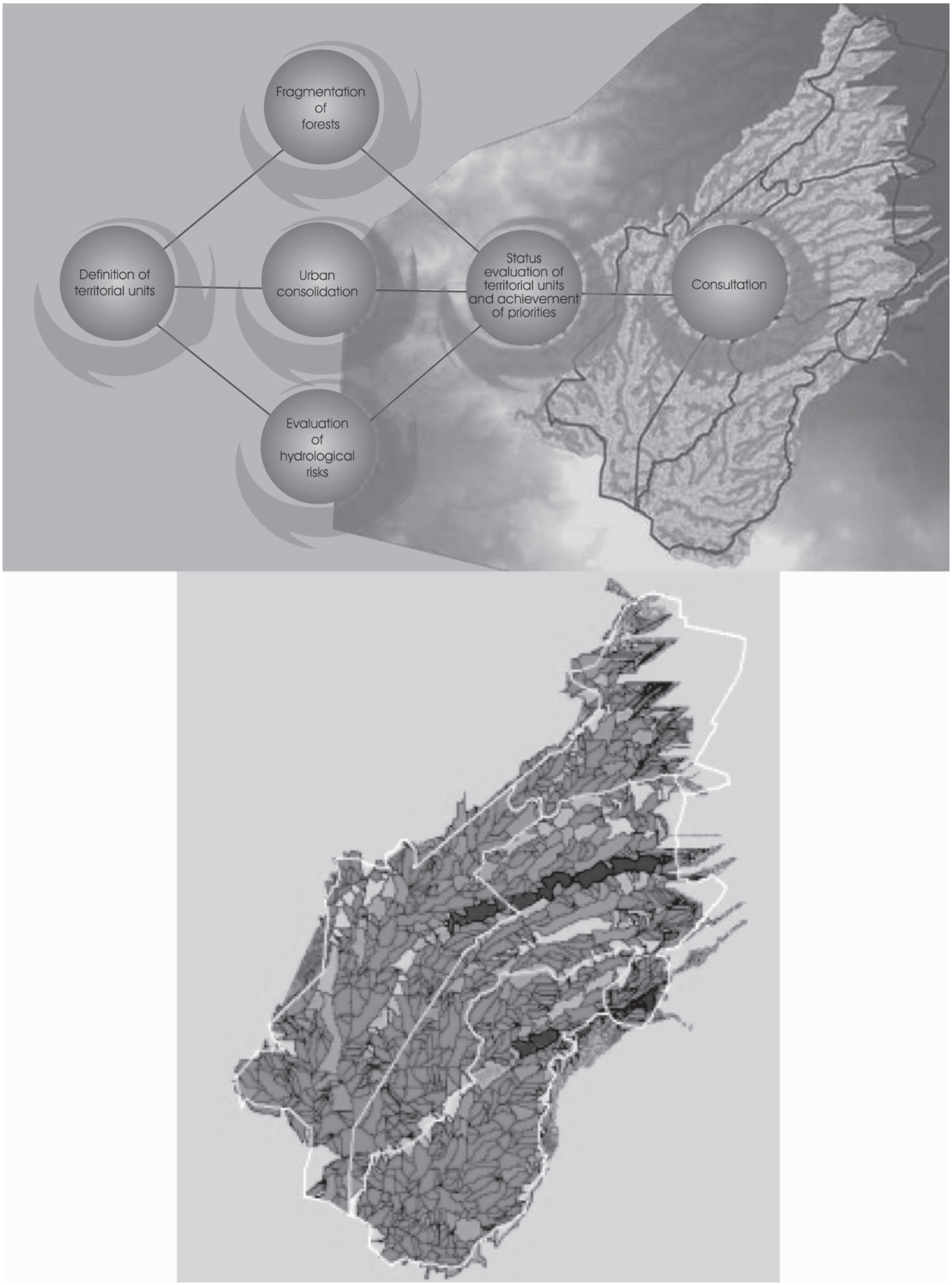
scenarios of the consequences of new management and organizational strategies for the processes studied. The process of generating new proposals supported by artefacts influences the evolution and transformation of the modelling system. Geomatic artefacts, especially versions that are educational or for the dissemination of information, such as those developed for Chapala Lake, have proved to be an effective means for communications about the problem and for raising public awareness about trends related to the degradation of society's resources. In addition, the internet represents a significant evolutionary change in geomatic artefacts, providing up-to-date investigations, with some of the artefacts currently available online, such as those related to the urban ravines in the western part of Mexico City (Tapia Silva et al., 2007c) and the Hydrographic Basins (figure 8.9).[2]

8.4 Conclusions

Studies conducted in the field of geomatics can provide knowledge and analytical methods that contribute to the process of improving the management of water resources. Spatial analysis techniques and obtaining information and knowledge through remote sensing allow for the study of hydrological and related variables, making it possible to identify appropriate solutions to specific conditions in the geographical regions studied. Geomatic artefacts are based on knowledge models and on a systemic and comprehensive perspective towards the problems to be resolved. They integrate information and knowledge from investigations based on remote sensing and spatial analysis, and may be geomatics' most significant contribution to raising public awareness and to the search for solutions. Through such artefacts, it is possible to generate second-order cybernetic processes that enable the definition of new alternatives for land management. The dissemination of these types of systems should be increased so as to maximize their potential for the management of water resources and for the generation of public policies and social initiatives that support the sustainable use and management of resources.

2 These can be accessed at: <http://xsei.centrogeo.org.mx/>.

Figure 8.9: Example of screens for the application of geomatics in the system for the management of ravines. **Source:** Tapia Silva et al. (2007c)



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9 Water Use for Agriculture in Mexico

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9.1 Introduction[1]

According to *Water Statistics in Mexico* (CONAGUA, 2008), 77 per cent of water is used for agricultural purposes although distribution across Mexico is poor. But knowledge of the spatial and time distribution of water used for irrigation purposes in Mexico is inadequate. Measurement of underground and surface water extraction for agricultural use is deficient at best, non-existent in most cases. The most trustworthy measurements are taken from irrigation districts, but the figures for water withdrawals in small irrigation units are unknown; estimates are taken from unreliable reports of irrigated surfaces reported by SAGARPA.[2] Because of the lack of measurement systems, groundwater extraction is estimated, often using questionable calculations.

The postgraduate *College of Agricultural Science* (COLPOS) has undertaken various research projects for the *National Water Commission* (CONAGUA) to estimate water use for irrigation across the country through various methods including the use of satellite images, electricity bills for pumping, sampling in irrigation areas, and volume measurements in different states throughout the country. This chapter summarizes some of the values obtained and the methodologies used for surface and groundwater measurements in each state.

Among the most important studies by COLPOS is one which estimates groundwater volumes used for irrigation in the aquifers of the Coast of Hermosillo and Janos, undertaken for the Directorate of Hydro-agricultural Infrastructure with the goal of estimating the water used for irrigation, based on remote sensing techniques and on-site sampling. More recently, in the Executive Project for Irrigation District 017 in the Comarca Lagunera, the research team used satellite images (SPOT, Landsat) to show the significant difference between water use for irrigation according to reported levels of concession permits for agriculture, and the actual volumes extracted. This documented the under-reporting in official SAGARPA reports. According to the results of these studies, the water extracted by irrigation districts is similar in magnitude to the volumes extracted by irrigation units, the difference lying in the extraction of groundwaters. Total water extraction for agricultural use was 60.7 km^3 in 2006, of which 20.1 km^3 came from groundwaters and 40.6 km^3 from surface waters.

9.2 Background

Despite the importance of water extraction measurements for controlling water use for each economic sector, it is possible that most of the water extracted from various sources is not measured. The sector that uses most water in Mexico is agriculture. Measurement of surface water extraction from dams and currents is acceptable, although there are no precise measurements of water extraction from deep wells, only estimates. Also, most small irrigation units are unmeasured, both in terms of surface and groundwater, so consumption is estimated according to the reports of irrigated surfaces.

Water extraction measurements at the urban-municipal level are also estimates; unfortunately they lack reliable information and tend to be inconsistent. Generally, there are no overall measures of water extraction in Mexico, and source metering is deficient, as the methods deployed are outdated and have been technically unreliable since the 1980's.

In 1997, the *National Water Commission* (CONAGUA) commissioned the postgraduate *College in Agricultural Science* (COLPOS) to evaluate the dimensions of irrigated surfaces and volumes of water used from the Pesquería River in the state of Nuevo León. Since the dimensions of the surfaces being irri-

1 Keywords: Water consumption, water measurements, water sources, irrigated areas.

2 SAGARPA is the Mexican Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food.

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_9,

gated with water from this river and the Ayancual Creek were unknown, the research team made a photo-mosaic of the region, as well as measurements of applied irrigation areas. Images from the satellite LANDAST 7 were also used together with software developed by the *Mexican Institute of Water Technology* (IMTA) in order to verify cultivated surfaces using the *normalized difference vegetation index* (NDVI).

In 1999 a thesis was produced (Bolaños, 2000) with the participation of the *International Irrigation Management Institute* (IIMI) and COLPOS. The aim was to evaluate the volume of water use and irrigation surfaces in the high basin of the Lerma River, using four images from Landsat 7. Through a survey of irrigation areas, measurements were undertaken on the main crops produced in that region. Images were treated using IDRISI software for the Microsoft DOS operating system.

Also in 1999, COLPOS undertook a study for CONAGUA to assess the volumes of water extracted in the aquifers of Janos and the Coast of Hermosillo, by applying remote sensing techniques using Landsat 7 images, and measurements of the irrigation areas for the crops of that region. Subsequently, the Directorate of Hydro-agricultural Infrastructure at CONAGUA entered into an agreement with COLPOS to evaluate the irrigated areas and especially small irrigation units across the country.

Since 1985 the General Directorate of Water Administration of the Ministry of Agriculture and Hydraulic Resources has been experimenting with a method of assessing the volumes of water pumped from deep wells through measurements of electricity consumption and the electromechanical efficiency of the pumping equipment. They defined different zones according to average efficiency extraction values in m^3/kWh. Employing this same method and based on energy consumption tariff 9M, reports from the *Federal Electricity Commission* (CFE), the *Coordination of Efficient Water and Energy Use* (CUEAE-SDGIH) evaluated groundwater extraction volumes in every state of Mexico in 1992. They published a manual for evaluating pumping equipment for deep wells, describing methodologies and extraction indexes for every state (CONAGUA, 1994). The methodology deployed in this study was used to estimate the irrigated surfaces and the volumes of water extracted in the *Annual Agricultural Report 2004–2005* for all irrigation units based on research by COLPOS for CONAGUA.

9.3 Objectives

This chapter will estimate the volumes of water extracted for agricultural irrigation from both surface and underground sources through pumping from deep wells in each state of Mexico. Given that there are not enough adequate measurements of these extractions, the study uses indirect methods to obtain the necessary data that are then compared with official data from CONAGUA to assess the methodological validity. Water use trends can also be evaluated by comparing available statistics from CONAGUA and SAGARPA. For this, estimates of extractions were calculated for the period 1998–2007. Based on this analysis, the authors propose actions for improving controls over water used for irrigation to reduce negative impacts on the environment, the economy, and all users of water in agriculture.

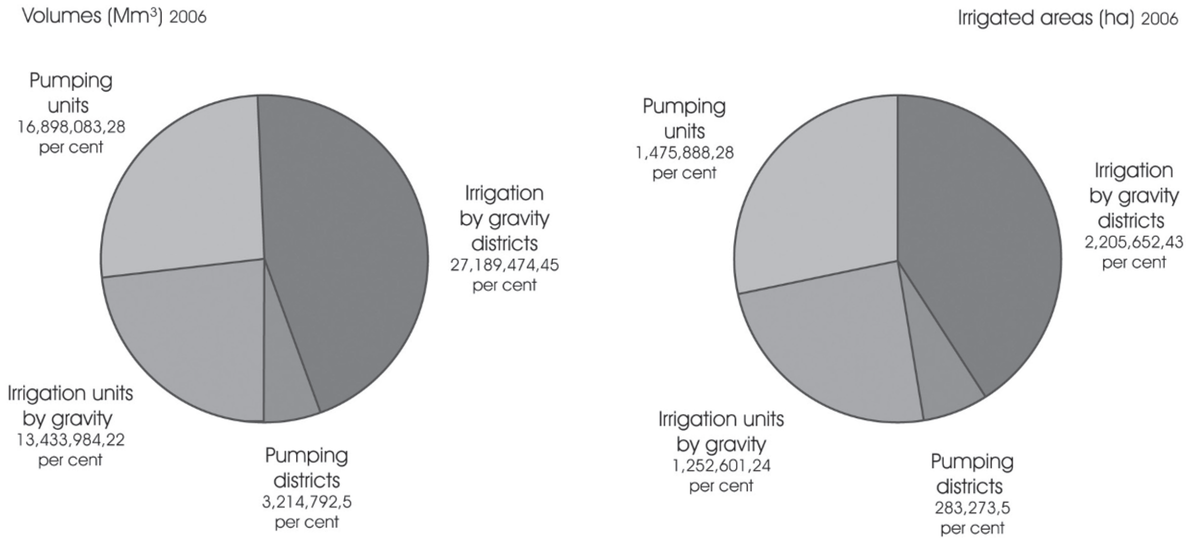
9.4 Methodology

For assessing the volumes of water used for irrigation in each state, both for irrigation districts and irrigation units, it is important to consider various hypotheses of mixed reliability that may offer an acceptable estimate. Two hypotheses are fundamental: 1) the statistics on irrigated areas by SAGARPA and CONAGUA are generally reliable, although they are questionable in many specific cases; 2) the average irrigation surfaces at the state level are representative of the average volume used per hectare for the main crops and thus are taken to estimate average volumes used per crop, which is also very controversial.

A joint study by COLPOS and CONAGUA of Irrigation District 017 Comarca Lagunera recorded that water consumption in areas with official irrigation permits was underestimated by at least 10 per cent (Bolaños et al., 2008), which severely questions the reliability of available agricultural statistics. It also showed that irrigation areas for different crops varied considerably for this irrigation district in their actual surface; usually their size was under-reported, and consequently more water was used. For groundwater extraction with deep wells, the base hypothesis is also questionable, as is the claim that it is possible to measure mean water volumes according to average kilowatts pumped using information from CFE. CONAGUA had previously scrutinized this hypothesis.

The methods proposed in this chapter for estimating water extraction volumes for agricultural irrigation deal with irrigated crops using wells. They rely on a

Figure 9.1: Distribution of irrigated areas and volume for each water source. **Source:** The authors.



proposal in a study by Cueae for CONAGUA in 1994 based on electricity consumption statistics for each state, provided in CFE reports with some adjustments as outlined below. By dividing the estimated values from this method by the irrigated surfaces (reported by SAGARPA), the average irrigation surfaces may be approximated. The average irrigated areas estimated may be compared with the measurements derived from actual surveys done by COLPOS.

CONAGUA annually supplies agricultural and hydrometric statistics at the district and state level for irrigation districts. Thus, the surfaces can be estimated, and if this information is compared with SAGARPA reports, it becomes relatively trustworthy. If the surface reported by irrigation districts is deducted from the total irrigated surface as reported by SAGARPA, one may calculate the surface of small irrigation units. But it is necessary to make adjustments to official data. For 2006, CONAGUA reported that in Baja California in Irrigation District 014 Colorado River, 197,247 hectares were irrigated, while according to SAGARPA the surface was 180,849 hectares. This difference for Irrigation District 014 reflects the fact that it includes a municipality from Sonora. Therefore, it is necessary to deduct the average irrigated surface in the municipality of San Luis Río Colorado from the total.

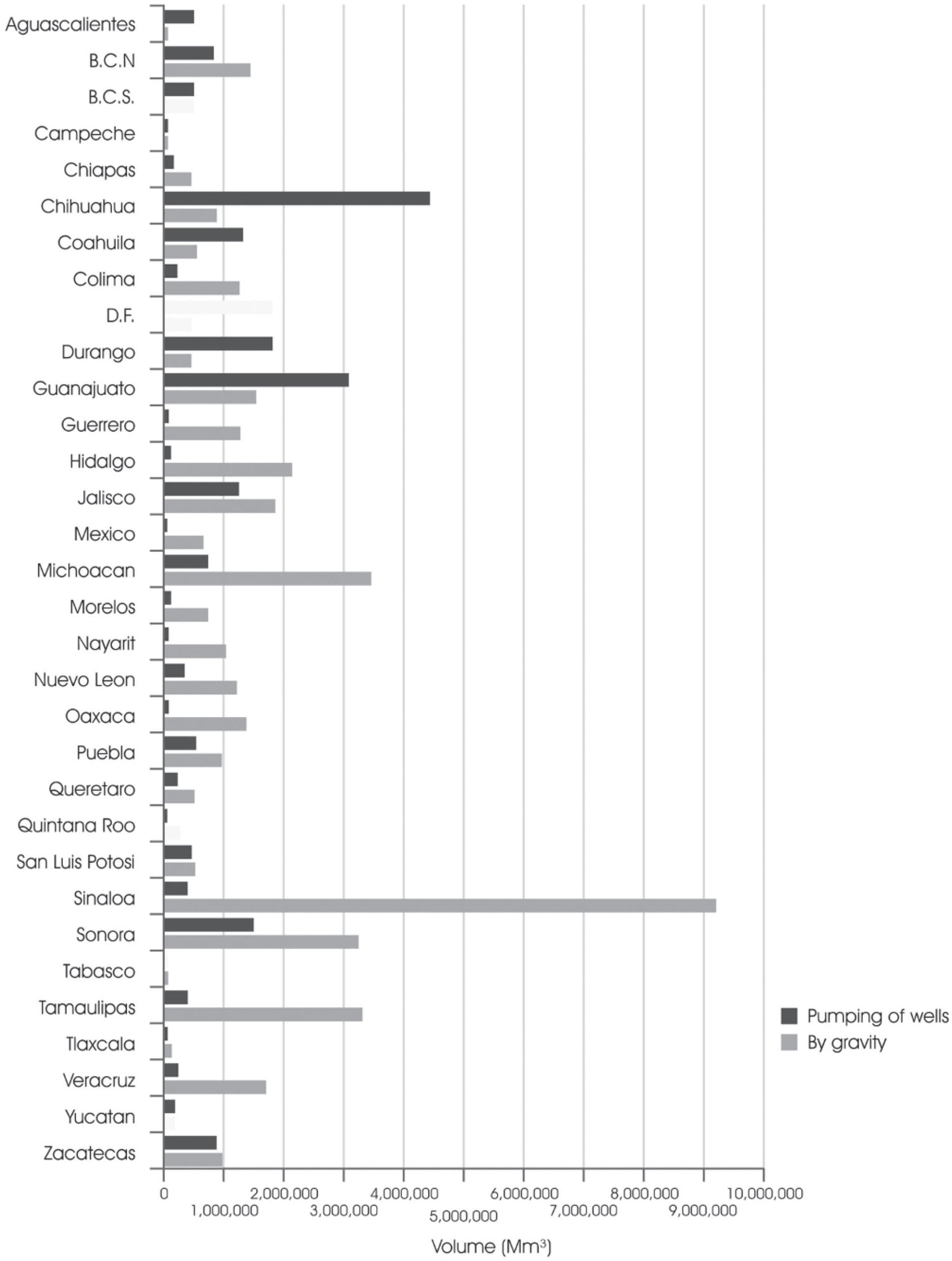
For CFE's electricity consumption reports, consumption was previously subdivided into high and low voltage. The latter corresponded to small wells for livestock and pressurized pumping systems. But part of the reported energy use corresponds to the pumping of flowing water, so a percentage must be deducted from the total to obtain proper consumption estimates for deep wells. In the original CFE reports approximately five per cent of the energy used was low voltage, and two per cent of high voltage was used for pumping from sources other than deep wells; and so the estimates were adjusted. Also, productivity indexes were adjusted to water volumes per kWh; they were usually reduced due to observed falling pumping levels.

9.5 Results and Discussion

The results obtained with these methods for water use in the agricultural sector for 2006 are shown in figures 9.1(a) and 9.1(b), displaying the distribution of volume and irrigated areas according to irrigation districts and units, at the national and state level (figure 9.2). The actual figures for each state are detailed in table 9.1. The total values of surface and groundwater extraction are congruent with CONAGUA's official statistics for 2007; approximately 40 km^3 relied on surface waters and 20 km^3 on groundwaters.

In the year 2006, the irrigated surfaces in districts and units are similar. They tend to be greater in irrigation units which have increased during the past 25 years, whereas surfaces in irrigation districts have declined (see below). Also, the total volumes of water used are similar, perhaps greater in irrigation districts, but the composition according to water source differs. Thus, while 56 per cent of water used in irrigation units comes from underground pumping, this fig-

Figure 9.2: Volumes of water extracted for irrigation according to source in each state according to the source (m3) for 2006. **Source:** The authors.

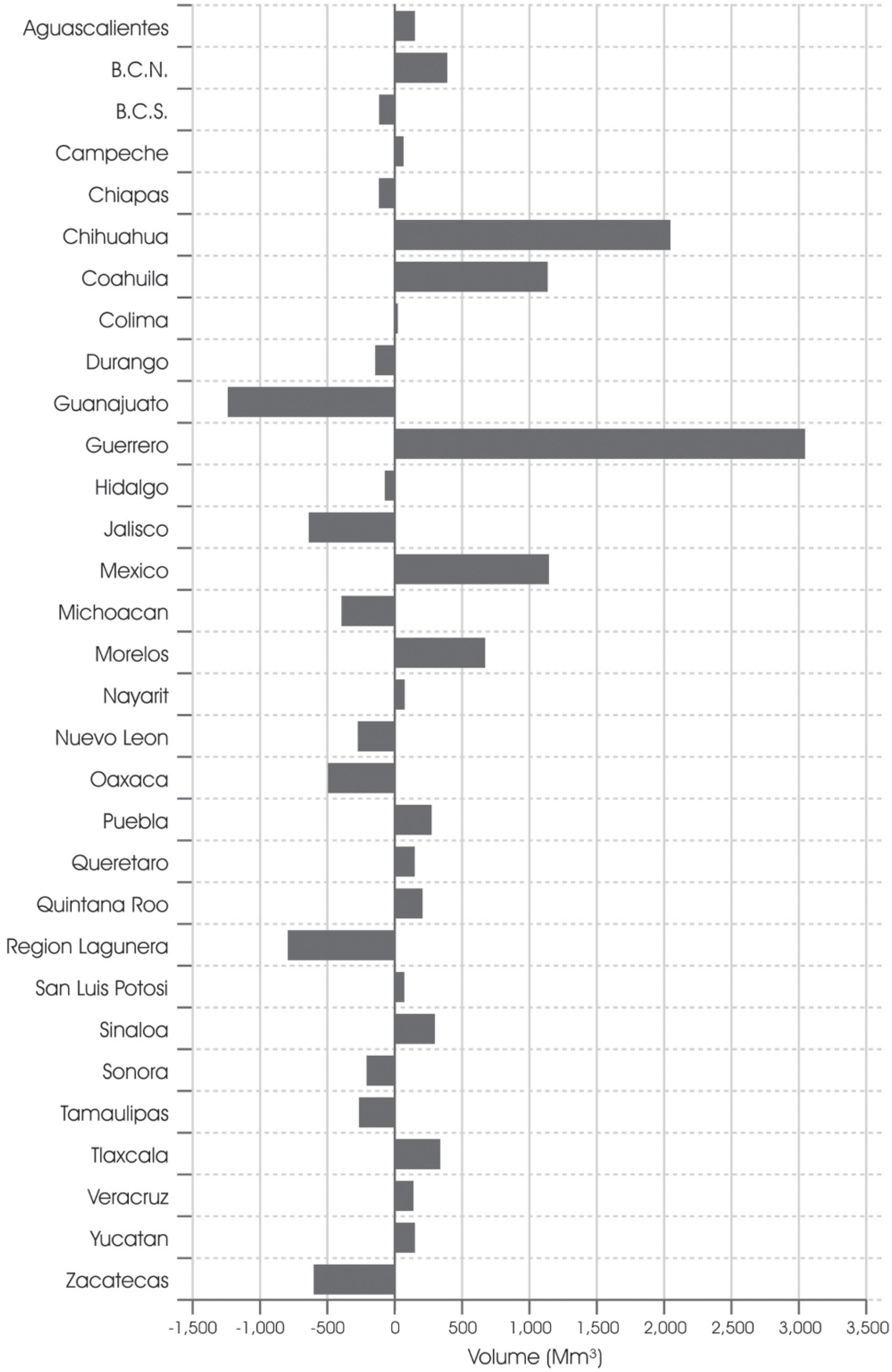


ure amounts to only 11 per cent for irrigation districts, where surface water predominates.

Based on official permits up to the year 2007, as reported by CONAGUA for each state, the volumes of water may be compared with the values obtained in this study. Figure 9.3 points to discrepancies in several states, as there is no complete record of extracted volumes due to a lack of measurements of both surface and groundwaters. However, the total differences are minimal except for some states, e.g. Durango.

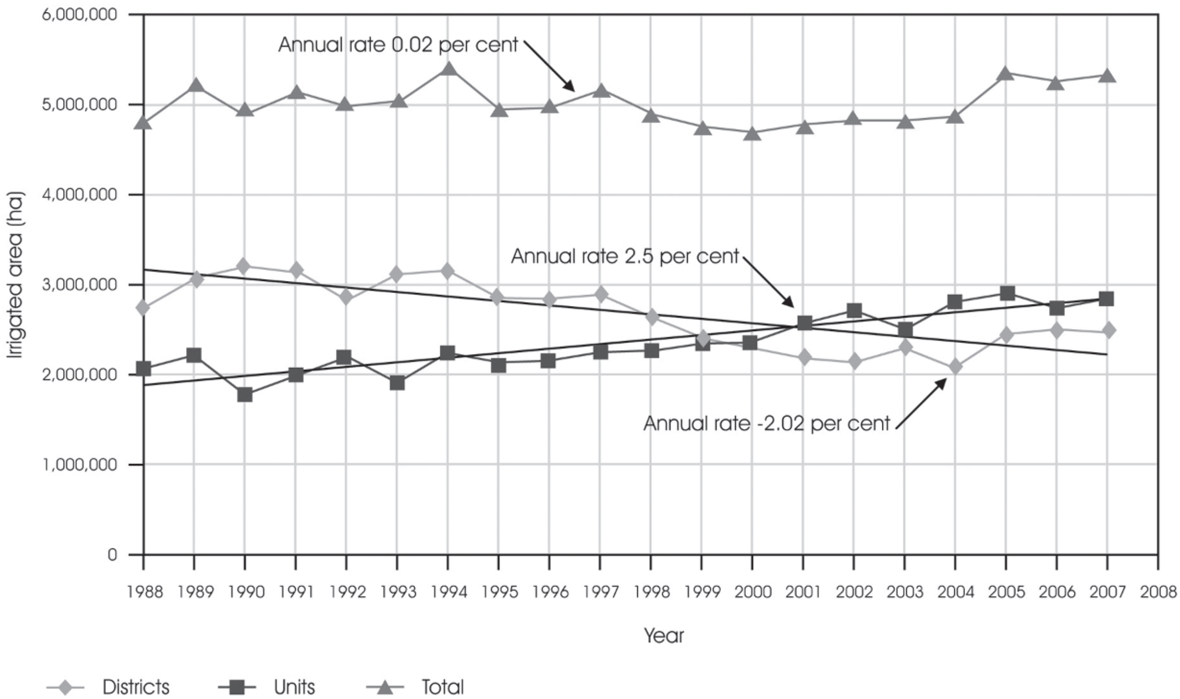
Comparing groundwater extraction for each state in 1992 (CONAGUA, 1994) with data for 2006, the authors observed an important increase in many states, such as Chihuahua, where the energy use for agriculture doubled, and for Durango and Jalisco, where it tripled. Major increases were recorded in Baja California Sur, Mexico, Querétaro, Sonora and Tlaxcala (figure 9.3).

Figure 9.3: Changes in volumes of groundwater extraction between 1992 and 2006. **Source:** The authors.



Following a similar procedure, irrigated surfaces in irrigation districts and small units were calculated, as well as water volumes from surface and underground sources for the past twenty years. The mean average growth rate per annum for each subsector was included. Thus, in figure 9.4 variations in irrigation areas may be observed at the district and small unit level between 1988 and 2007.

Figure 9.4: Variation of irrigated areas according to Irrigation Districts and Irrigation Units in Mexico (1998-2007). **Source:** The authors.



The total irrigated surface area did not grow as much during the past twenty years since the foundation of CONAGUA, despite the large number of public works that were carried out, including storage and dams, pumping plants and deep wells. Irrigated surfaces in irrigation districts have declined, even if the contrary has occurred in small irrigation units. The reduction in irrigated surfaces in irrigation districts, despite the increase in the total number of irrigation districts, is due to the fact that surface water used for irrigation in small units has come from the supply sources of the districts, as has been documented in some regions by COLPOS studies.

The variation in water volumes used for irrigation over two decades, both for surface and underground sources, is illustrated in figure 9.5. Surface water use slightly declined, whereas for groundwater a major increase occurred during the same period, due to increased numbers of wells and over-exploitation of aquifers. Energy consumption for agriculture has notably increased in this period.

The use of electricity for irrigation has steadily increased since 1962 based on CFE data. Between 1962 and 1989 energy consumption increased annually by an estimated 9.79 per cent. But from 1990 energy tariffs increased considerably, and this had an impact on consumption. Since 1993 tariffs have been adjusted and consumption has moderately increased. From 1988 to 2007, energy use increased by 1.22 per cent annually. Also, the number of users has increased more rapidly than consumption; thus, during the first stage from 1962 to 1989 the average annual growth rate of users was 10.76 per cent, whereas in the second period from 1988 to 2007 it was 2.43 per cent, almost double the rate of consumption. Figure 9.6 shows the variations in consumption (MWh) and number of users.

As can be seen for the past few years, energy consumption has stabilized at 7.5 million megawatts per hour even though the number of users has increased, indicating a decrease in the average consumption per user. This could have two causes; the first, possibly a more efficient use of electric energy due to activities by CONAGUA to improve efficiency of electromechanical equipment; and the second, a part of the consumption was for low pressure pumping, for example drip irrigation (figure 9.5).

Also, the apparent diminution of irrigated areas in organized districts during the past twenty years is worrying, especially as the number of irrigation districts has increased. However, CONAGUA's annual reports show a diminution in irrigated areas in most states. In figure 9.7 the average growth variations of irrigated surfaces for each state are shown graphically and ap-

Figure 9.5: Variation in volumes of water used for irrigation according to source. **Source**: The authors.

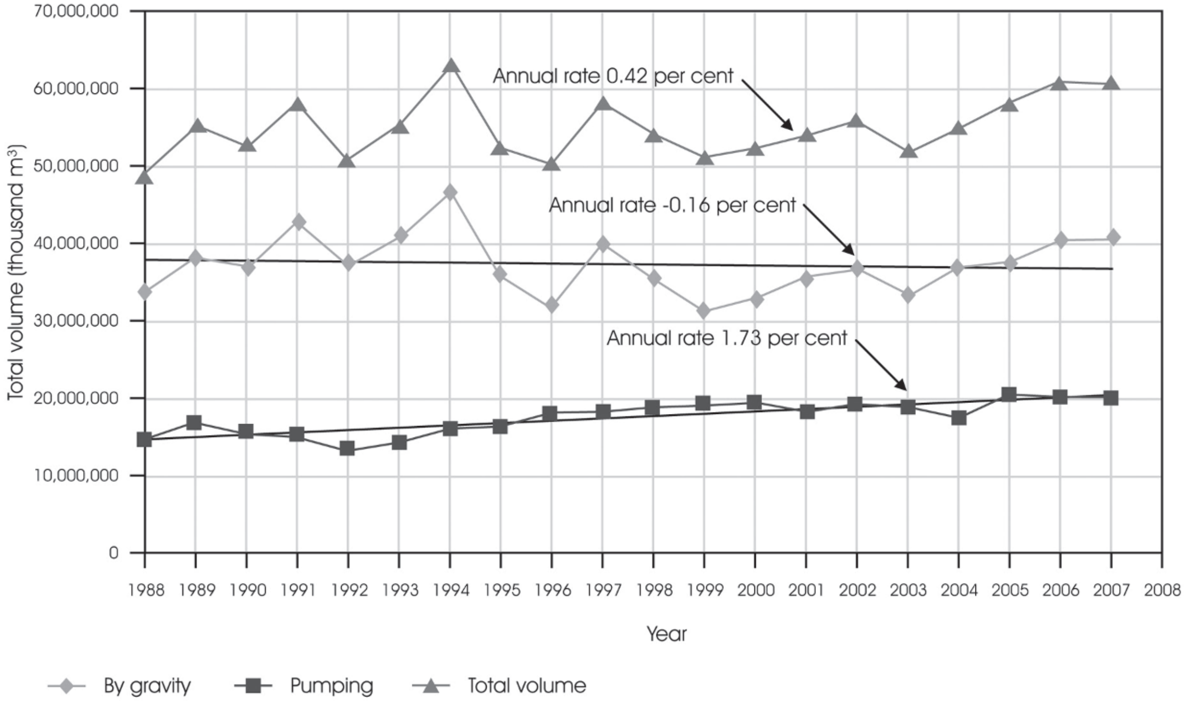
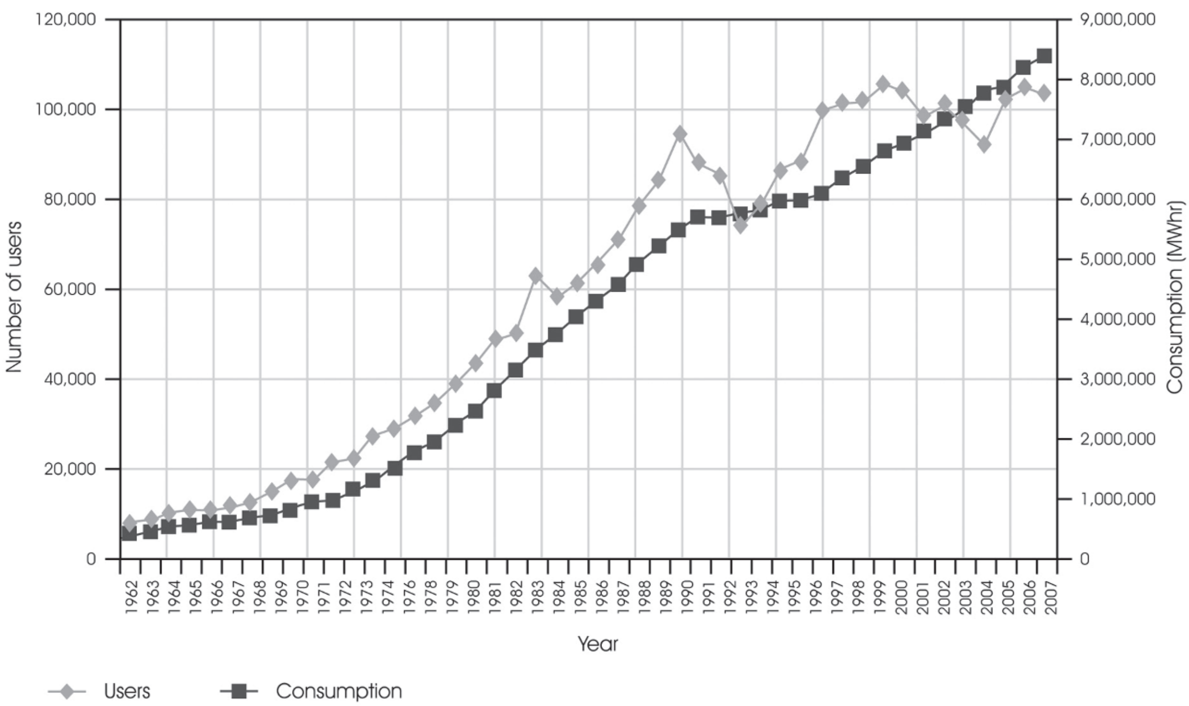


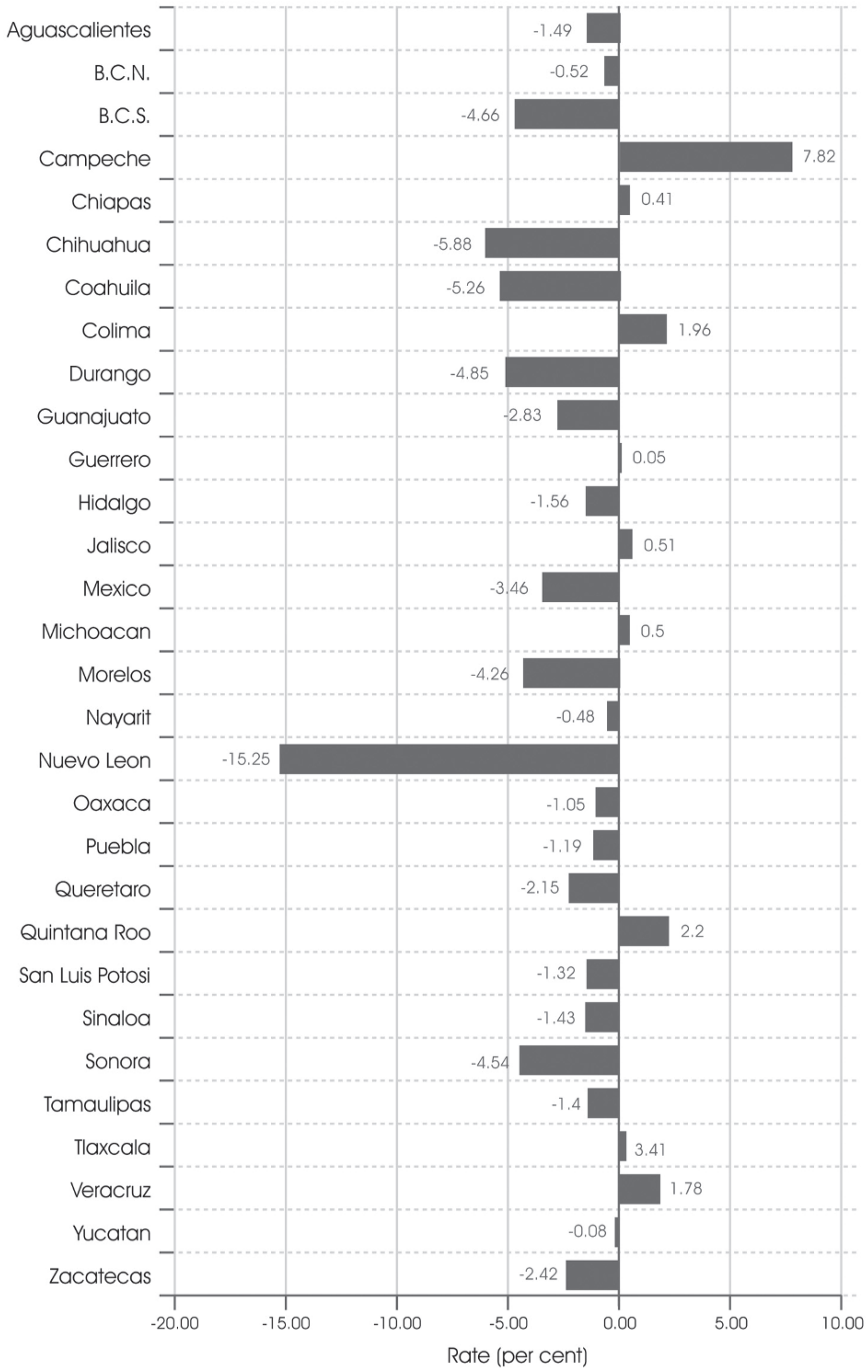
Figure 9.6: Variations in energy consumption (MWh) and number of users in the agricultural sector, 1962- 2007. **Source**: The authors.



pear to be negative, except in Campeche, where the irrigation district by pumping source became a small irrigation unit.

However, there has been an increase in small irrigation units, as well as a rise in users of surface water and groundwater, which has compensated the former

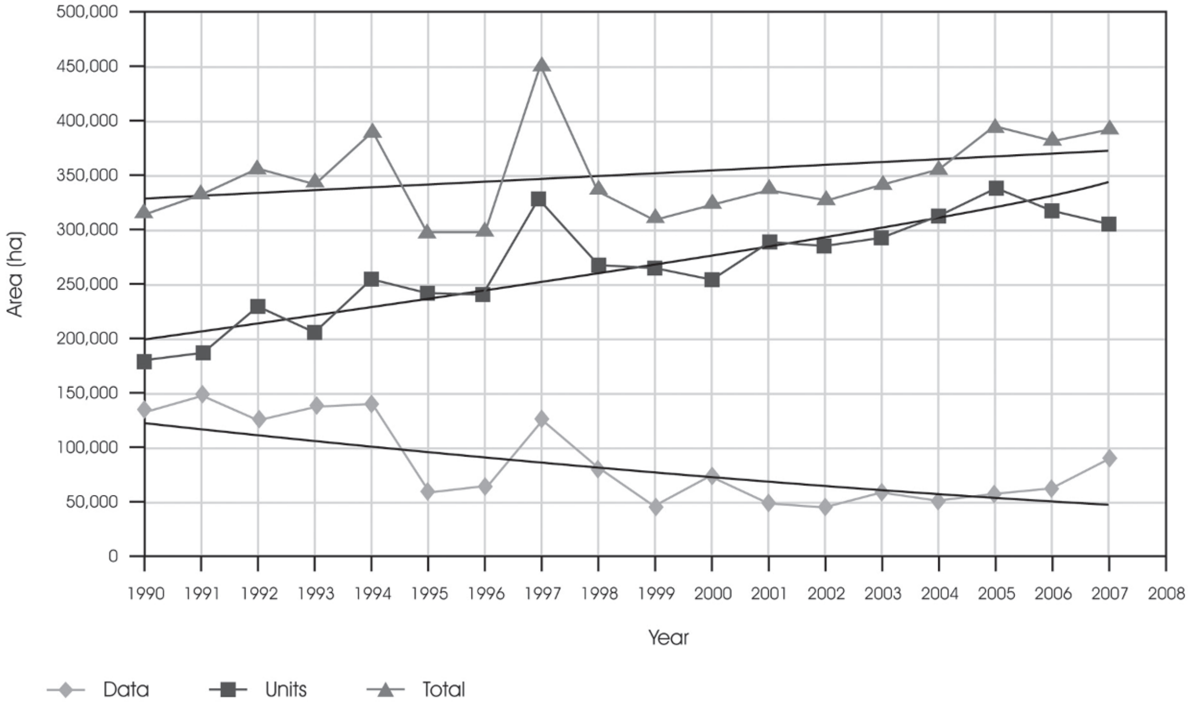
Figure 9.7: Average growth variation of irrigation areas contrasted with irrigation districts for each state. **Source**: The authors.



trend in irrigation districts. This means that water previously used for irrigation in districts is currently being used for micro-irrigation, and that groundwater extraction by deep wells has increased.

An important example of this is the state of Chihuahua, where the surface irrigated in districts has considerably decreased (figure 9.7), with an annual variation rate of -5.88 per cent, but the rise of overall

Figure 9.8: Variation of irrigation areas in the State of Chihuahua. **Source**: The authors.



irrigated surface of the state is positive (0.7 per cent annually). This is caused by water use in irrigation units, especially with wells, which have increased by 3 per cent per annum, implying an increase in energy consumption and in groundwater extraction. To illustrate this specific example, figure 9.8 shows how irrigated surfaces have varied in the state of Chihuahua, a case where irrigation has shifted from the irrigation districts to smaller irrigation units.

From a legal, environmental and economic perspective, an important problem is the building of an irrigation infrastructure without thoroughly evaluating its impact. This affects users by undermining their rights, the environment if works negatively impact on regions, and the economy as investments might have negative productivity.

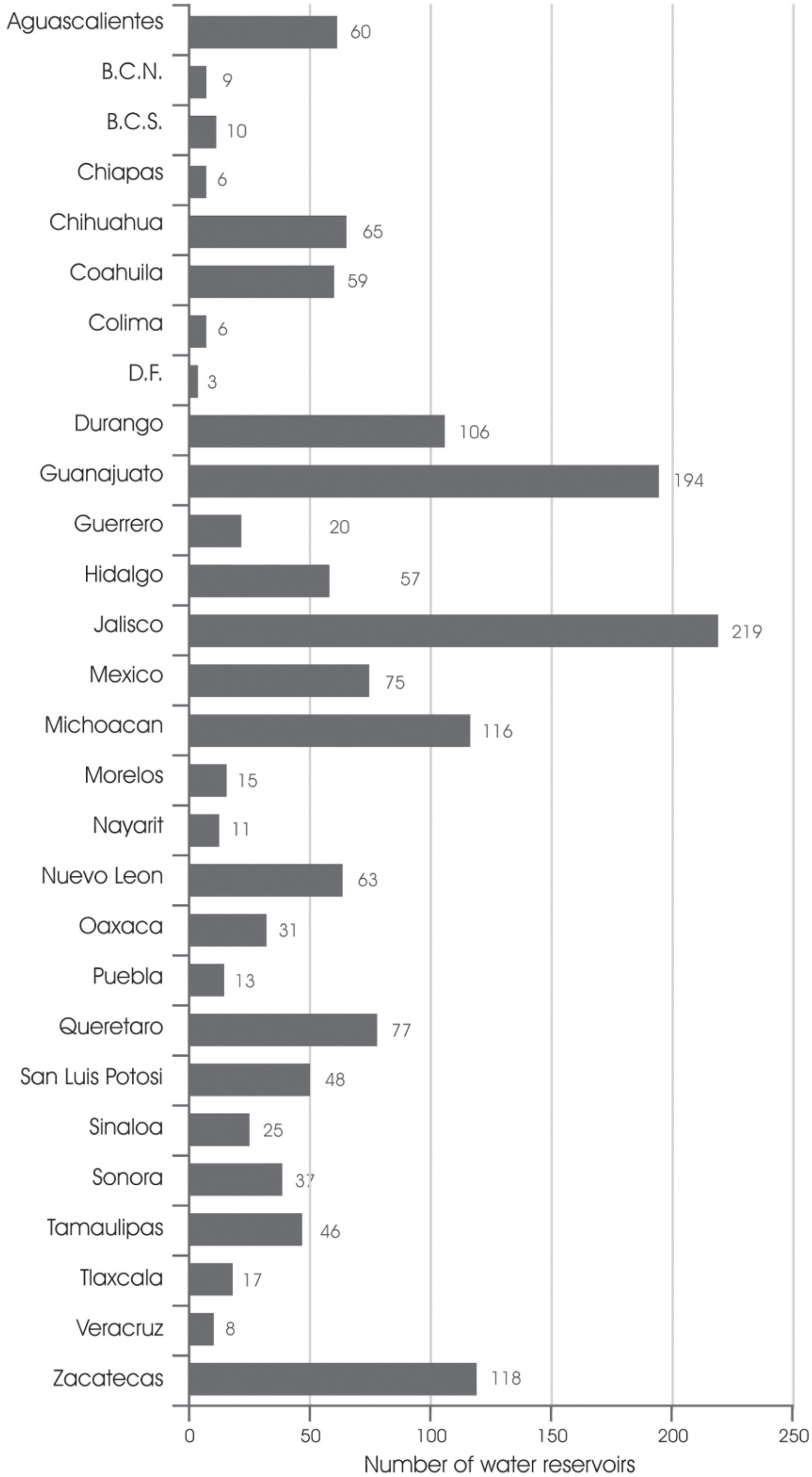
A well known example is the construction of the dam El Molinito in the River Sonora, upstream from the dam Abelardo Rodríguez, and close to the city of Hermosillo. This dam stopped the waters from arriving at Rodríguez dam, which operated as one of the prime water sources for the city and as a thermal regulator, given that water evaporation in the dam positively impacted on the high summer temperatures. With the construction of the new dam, water flows in the aquifer of the Coast of Hermosillo were significantly reduced, and agriculture in the region of the high basin was favoured, further reducing surface and underground run-off downstream.

These types of problems became generalized due to a lack of thorough studies on the environmental impact of irrigation works. COLPOS undertook various studies in the River La Laja basin in Guanajuato where the negative impacts of irrigation infrastrucutre and well drilling in the high basin were demonstrated (Palacios, 2004). During the last twenty-five years the construction of new water infrastructure has affected the water users and the environment, generating conflicts between regions and producing reduced irrigation surfaces in many areas of the country.

According to CONAGUA reports, during the past twenty years infrastructure was built for up to 20 thousand hm^3, but the present study shows that the overall irrigated surface remained constant, with 5 million hectares being cultivated annually on average (variations are mainly due to weather conditions). The problem has been the construction of too many dams, with water contention walls and dykes generating water losses due to evaporation and to upriver dams curtailing flows downstream. Thus, works that benefit small irrigation units have reduced water sources for irrigation districts.

According to CONAGUA's database, Mexico has more than 15,000 reservoirs with a capacity of more than 0.5 hm^3, with an overall total capacity estimated

Figure 9.9: Number of dams with a capacity of over 0.5 hm^3 by state. **Source**: The authors.



at over 150,000 cubic hectometres; this includes important dams used for hydroelectric generation, but the proportion is much higher for smaller dams used for irrigation. Some states have more than a hundred (figure 9.9).

Besides dams, there are also a high number of levees and irrigation channels with different capacities; they are mainly used for irrigation and livestock. SAGARPA, through its programme of micro-basins, has supported the building of these levees and irrigation channels, which keep run-off waters from reaching dams. For example, in Guanajuato, besides the 194 dams registered by CONAGUA, there are 830 levees and irrigation channels in the various municipalities of the state.

So far there is no agreement between SAGARPA and CONAGUA on guidelines for authorizing the construction of levees and irrigation channels. CONAGUA itself builds new water dams upriver in the same streams where there are other dams, affecting the rights of users of irrigation districts and small irrigation units.

It is worrying that many hydraulic works built by CONAGUA lack adequate environmental impact studies. Often, they have only assessed their most apparent benefits, neglecting any broad negative impact or environmental externalities. Another worrying fact is that CONAGUA provides faulty reports on irrigation surfaces to international institutions such as FAO, based on areas that according to CONAGUA are suitable for irrigation but are not actually irrigated. Thus, according to National Water Statistics 2008, the irrigated surface in Mexico is reported as 6.46 million hectares. Such an area has never been irrigated; the maximum surface that has been irrigated, including primary and secondary crops, has been 5.41 million hectares in 1994. This means one million hectares less than what is reported. Furthermore, the area suitable for irrigation is estimated by experts at less than 5 million hectares, despite new irrigation works being inaugurated every year.

In a study undertaken by COLPOS and CONAGUA (1998) on the surface that could be suitable for irrigation within irrigation districts – based on data directly provided by the personnel responsible for operations in the districts – the figure for the area having sufficient water was estimated at 3.1 million hectares. Thus, the annual water availability in some irrigation districts did not enable all available infrastructures to operate.

It would possible to increase the irrigated surfaces if it were possible to enhance water use efficiency, for which it would not be necessary to create more irrigation districts or units, but rather to make better use of the available infrastructure. Generally, water use efficiency is considered to be low, although it would be important to undertake more detailed studies on the real efficiency of water use.

Information on the efficiency of water-carrying devices such as pipes or ducts exists, but it is not very reliable. Water supply is not measured when it arrives at the irrigation fields. Looking at the variation patterns in data reported by CONAGUA on water-carrying efficiency in irrigation districts (figure 9.10) in the period between 1985 and 2005, it is difficult to identify possible causes. It is assumed that data are more reliable after 1990 when estimates were made by CONAGUA; but even then there is a significant increase from 1990 up to 1996, with a decline in 1997 and 1998, rising again in 1998 and falling again from 1999 onwards. Perhaps this is due to under-reporting by organizations of water users, called also 'administrative losses'.

If we analyse losses in terms of water-carrying efficiency in each irrigation district, there are some that do not have significant reductions, for example Irrigation District 014 Colorado River and Irrigation District 038 Mayo River. They have negative variations of up to 10 per cent, indicating that a part of these losses are indeed administrative losses.

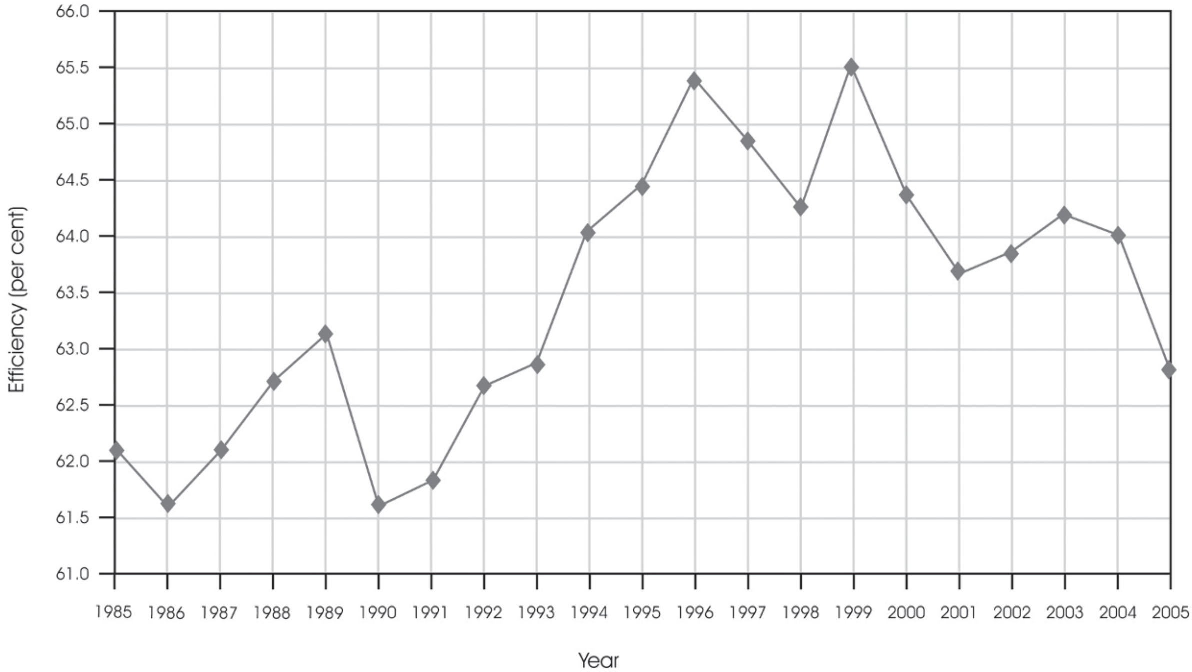
Also, we must consider irrigation districts in the inner part of Mexico, where the water is not really lost, because the run-off can be used downstream, and it recharges aquifers via infiltration. As for losses due to mismanagement in the actual irrigation fields, there is not enough information to make a reliable assessment. However, in some irrigation districts a considerable volume of water is lost due to poor irrigation practices. However, in many cases this trend is reversing because farmers are realizing that with efficient use of water they not only save water but also achieve greater productivity.

Improvement in water management focused on the distribution networks and on actual irrigation methods is a way of increasing irrigation areas without heavy investment. However, this requires the implementation of improved techniques, including efficient structures in the distribution network, levelling lands, and applying the most efficient irrigation methods.

9.6 Conclusions and Recommendations

Estimates of water use for agriculture in Mexico rely on methods used by CONAGUA. They show that irrigation areas in irrigation districts have been reduced

Figure 9.10: Conveyance efficiency reported by irrigation districts. **Source:** The authors.



at the same time as areas irrigated in small units have increased. These trends have allowed the overall irrigated surface to remain constant for the past two decades, with only minor variations caused mainly by weather conditions, as there is less surface water available in dry years.

Available annual surface water volumes have also decreased, which has led to an increase in groundwater use, especially through deep well pumping. Thus, many of the most important aquifers in the centre and north of Mexico have been over-exploited. Diminishing surface waters are not only caused by climate conditions, they are also related to evaporation in irrigation infrastructure and to the decreased runoff either because water is used in the upstream basin or because part of the waters used for irrigation is destined for other purposes.

Here, it is pertinent to note that water from wells used for irrigation has certain advantages over surface water, for example time and space, because farmers can make use of it when crops need it. This is not always possible with surface water, especially in irrigation districts where water availability is limited, either because water is insufficient or because water-carrying networks are inadequate to meet demand on time. Besides, some localized irrigation methods cannot be properly maintained in most irrigation districts.

Given energy tariffs subsidized by CFE, it is still possible for agricultural producers to irrigate the least profitable crops without economic losses; this policy produces an over-use of groundwater, and this is why pumping water has become more popular.

Currently there is not enough control over the distribution, efficiency, and use of water. The National Water Law has important limitations, including lacking a definition of what water rights are. Users of water for irrigation often lack legal security over the water volumes allowed by official permits. In other countries, water rights are clearly defined as the volume of virtual water estimated according to mean water availability in basins (statistically defined as a 50 per cent probability, not as an arithmetical measure), and every year water authorities estimate mean availability in order to fix greater or lower volumes to match official user permits.

Increasing irrigation areas without having enough available water poses a threat to all water users who currently have a right over that water and who see water availability decreasing. This situation is already present in many over-exploited basins, and it constitutes one of the causes of the decline of surface water for agricultural irrigation.

It is important to measure water properly when it is distributed, not only in agriculture, but in every sector, in order to make a fair allocation of water resources, and to ensure that the National Water Law is obeyed. Besides, it is important to provide water to users by volume so that they can save water for example from one agricultural cycle to the next. This would ensure efficiency and at the same time boost productivity. A strictly regulated market of water rights would also be an alternative.

Despite all factors that have been addressed in this chapter, irrigation agriculture has a great potential. While water use efficiency is currently low, it could be enhanced by using appropriate practices. Agricultural productivity could be doubled with the water and infrastructure currently available. Technology exists to improve crop productivity significantly, increasing the production of foods and raw materials. Unfortunately, this technology has not been accessible to most users in the agricultural sector, which is why the government, together with user organizations, technological centres and universities, disseminates this knowledge. A minor investment in these terms would be greatly beneficial to water users and to the entire country.

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Annex 1: Areas and volumes used in irrigation units and districts in 2006. **Source**: The authors.

	District (ha)			Units (ha)			Total area (ha)	Districts hm^3			Units hm^3			Total volume
State	Area	Pumped area	Total area	Area	Pumped area	Total area	Irrigated area	Volume	Pumped volume	Total volume	Volume	Pumped volume	Total volume	Irrigated volume
	Districts)	Districts	Districts	Units (ha)	Units (ha)	Units (ha)	Units +Districts	Districts hm^3	Districts hm^3	Districts hm^3	Units hm^3	Units hm^3	Units hm^3	Units +Districts hm^3
1. Aguascalientes	3,500	3,908	7,408	386	39,774	40,160	47,568	25,271	37,057	62,328	4,036	443,442	447,479	509,807
2 Baja California	100,990	66,049	167,039	3,090	10,719	13,810	180,849	1,390,298	799,775	2,190,073	32,309	6,294	38,603	2,228,676
3 Baja California Sur	0	27,316	27,316	1,520	5,778	7,298	34,614	0	152,693	152,693	12,917	112,060	124,976	277,669
4 Campeche	0	0	0	8,476	7,987	16,464	16,464	0	0	0	68,657	64,698	133,356	133,356
5 Chiapas	23,268	0	23,268	13,833	14,335	28,169	51,437	300,258	0	300,258	155,762	161,417	317,179	617,437
6 Chihuahua	50,420	15,022	65,442	140	319,495	319,635	385,077	880,728	192,276	1,073,004	2,032	4,256,794	4,258,827	5,331,831
7 Coahuila De Zaragoza	37,835	0	37,835	1,359	97,010	98,369	136,204	532,606	0	532,606	15,821	1,309,636	1,325,457	1,858,063
8 Colima	26,762	0	26,762	35,960	14,948	50,908	77,670	744,874	0	744,874	521,744	216,877	738,621	1,483,495
9 Mexico City	0	0	0	2,294	212	2,507	2,507	0	0	0	24,090	3,205	27,296	27,296
10 Durango	36,367	1,468	37,835	3,913	98,666	102,579	140,414	380,292	14,337	394,629	47,352	1,768,041	1,815,393	2,210,022
11 Guanajuato	58,953	44,588	103,541	97,018	269,602	366,619	470,160	568,959	431,456	1,000,415	950,772	2,647,603	3,598,375	4,598,790
12 Guerrero	17,801	0	17,801	59,736	2,908	62,643	80,444	421,608	0	421,608	848,248	37,217	885,465	1,307,073
13 Hidalgo	75,780	0	75,780	50,160	7,526	57,687	133,467	1,391,306	0	1,391,306	737,267	110,622	847,890	2,239,196
14 Jalisco	49,392	0	49,392	78,420	93,084	171,504	220,896	777,009	0	777,009	1,072,872	1,273,488	2,346,359	3,123,368
15 State Of Mexico	16,334	0	16,334	125,190	15,952	141,143	157,477	94,602	0	94,602	543,207	69,217	612,423	707,025
16 Michoacán De Ocampo	153,579	17,092	170,671	148,745	54,410	203,156	373,827	1,924,454	130,351	2,054,805	1,508,102	594,598	2,102,700	4,157,505
17 Morelos	20,449	0	20,449	21,261	4,042	25,303	45,752	467,670	0	467,670	270,018	91,191	361,209	828,879
18 Nayarit	22,060	0	22,060	38,882	1,755	40,637	62,697	415,339	0	415,339	608,604	27,469	636,074	1,051,413
19 Nuevo León	13,247	0	13,247	64,085	21,238	85,323	98,570	235,837	0	235,837	943,041	312,523	1,255,564	1,491,401
20 Oaxaca	24,886	0	24,886	54,208	2,687	56,895	81,781	698,865	0	698,865	677,598	59,564	737,162	1,436,027
21 Puebla	19,553	0	19,553	67,674	56,637	124,311	143,864	234,941	0	234,941	682,383	571,085	1,253,467	1,488,408

	District (ha)			Units (ha)			Total area (ha)	Districts hm^3			Units hm^3			Total volume
State	Area	Pumped area	Total area	Area	Pumped area	Total area	Irrigated area	Volume	Pumped volume	Total volume	Volume	Pumped volume	Total volume	Irrigated volume
	Districts)	Districts	Districts	Units (ha)	Units (ha)	Units (ha)	Units +Districts	Districts hm^3	Districts hm^3	Districts hm^3	Units hm^3	Units hm^3	Units hm^3	Units +Districts hm^3
22 Querétaro De Arteaga	1,000	6,155	7,155	32,187	8,535	40,722	47,877	20,526	34,758	55,284	450,612	170,908	621,520	676,804
23 Quintana Roo	0	2,700	2,700	0	401	401	3,101	0	23,566	23,566	0	3,810	3,810	27,376
24 San Luis Potosí	20,794	0	20,794	38,535	57,056	95,591	116,385	190,924	0	190,924	288,772	427,562	716,334	907,258
25 Sinaloa	702,932	0	702,932	52,028	43,084	95,113	798,045	8,734,461	0	8,734,461	471,128	390,138	861,266	9,595,727
26 Sonora	322,911	91,155	414,066	27,498	57,273	84,771	498,837	3,005,224	1,363,021	4,368,245	216,436	121,261	337,697	4,705,942
27 Tabasco	0	0	0	3,601	1,367	4,968	4,968	0	0	0	30,607	11,624	42,230	42,230
28 Tamaulipas	350,424	0	350,424	74,880	61,743	136,623	487,047	2,857,798	0	2,857,798	432,032	356,233	788,265	3,646,063
29 Tlaxcala	4,030	0	4,030	16,180	7,136	23,316	27,346	22,191	0	22,191	77,982	34,392	112,374	134,565
30 Veracruz-Llave	42,464	0	42,464	63,643	298	63,941	106,405	746,768	0	746,768	941,700	237,920	1,179,620	1,926,388
31 Yucatán	0	7,820	7,820	2,175	26,508	28,683	36,503	0	35,502	35,502	17,618	129,273	146,892	182,394
32 Zacatecas	9,921	0	9,921	65,521	73,721	139,242	149,163	126,665	0	126,665	780,266	877,921	1,658,187	1,784,852
Totals	2,205,652	283,273	2,488,925	1,252,601	1,475,888	2,728,489	5,217,414	27,189,474	3,214,792	30,404,266	13,433,984	16,898,083	30,332,067	60,736,333

10 Social Problems with the Agricultural Use of Urban Wastewater

Francisco Peña

10.1 Introduction[1]

Social scientists have taken an interest in the distinct components of federal water management policies, often following what government officials were already focusing on. More attention has been paid to recording water rights, the modification of all usage rates, especially domestic use, and the formation of entities for shared responsibility with users within water management e.g. with the establishment of the *Consejos de Cuenca y Comités Técnicos de Aguas Subterráneas* (Watershed Councils and Technical Committees for Subterranean Water). Other issues, such as that of reusing water in safe conditions and assessing the progress of watershed treatment, have remained in the background. Often current or trustworthy general information about these issues is lacking. This chapter assesses the agricultural reuse of urban wastewater, focusing on the case of the Valle del Mezquital in Hidalgo, but also analysing findings about other examples in the country, which are limited. It is this simultaneous assessment of irrigation with wastewater and the research on this phenomenon that has been conducted in Mexico by social scientists.

The agricultural use of water discharged from cities has important environmental, economic and social impacts; this has been the basis of conflicts that have arisen in Mexico during the past two decades. Organized communities have vigorously protested in favor of the agricultural use of wastewater (which in some cases has been used for more than a century, as in the case of Mezquital or San Luis Potosí), and are against being the recipients of urban waste that contaminates their rivers and properties. This chapter discusses the different types of locally organized social resistance groups that clarify, halt or modify government actions, bringing into question the State's capacity to regulate the use of quality water for irrigation for overall health; the social argument is for the quantity and quality of water that is received. These issues are examined below:

1. The assessment of wastewater irrigation as a foundation of agricultural development, related to rural and urban development policies that seem to have collapsed.
2. The characterization of the parties in these conflicts, both those who support the cases of consolidated irrigation with wastewater and those who defend clean water for crops.
3. The assessment of public performance, marked by the sluggishness of water treatment processes which clearly delay planned work, and demonstrate the impossibility of implementing the current legal framework.
4. A research agenda that links the regional water crises with the collapse of national agriculture.

10.2 Objective

This chapter offers an assessment of the agricultural reuse of urban wastewater and of the reasons why this topic must be systematically addressed by social scientists researching water use in Mexico. Social scientists must be able to respond to these frequently asked questions: Why have the proposed treatment techniques not been carried out? Why are their results so scarce? This chapter also shows that the social argument focuses both on the quantity and quality of the water received; it does not discuss the proposed treatment techniques, but rather the reasons why these proposed techniques are not put into operation by government agencies and/or are rejected or seen as untrustworthy by different local farmer groups, and why they fail.

1 Keywords: irrigation and conflicts, watershed treatment, wastewater.

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_10,

10.3 Urbanization and Irrigation with Urban Wastewater

While agricultural irrigation with wastewater from domestic origins and the use of excrement and other organic waste as fertilizers are very old, this chapter only discusses irrigation based on vast increases in land treated with concentrated urban wastewater. This method is more recent and its importance and dissemination began during the second half of the 19th century.

The method of irrigating crops with wastewater began in Paris in 1868 as a means of decreasing the contamination of the River Seine downstream, which was also seen as a way of treating wastewater. By 1872, close to 900 hectares of land surrounding the French capital were being irrigated with this technique. In 1904 some 5,300 hectares benefited, a third of which were city properties that were rented to settlers 6reusing countries:

- In Great Britain in 1875 about 50 places used wastewater for irrigation, including Edinburgh.
- In Mexico wastewater from Mexico City has been used for irrigation since 1886 in the Valle del Rio Tula.
- In Australia in 1892 the first agricultural area was irrigated with wastewater from Melbourne.
- In France in 1904 about 5,300 hectares surrounding Paris were irrigated with wastewater from the city.
- In the United States in 1904 urban wastewater was used for agricultural irrigation in 40 sites, although the earliest example dates back to 1871 in Lenox, Massachusetts.
- After the construction of a sewerage system in Santiago in Chile in 1908, wastewater was pumped into the Zanjón de la Aguada and the Rio Mapocho, that flow into the Rio Maipo. This water was immediately used for agriculture.
- In Germany in 1910 some 17,200 hectares were irrigated with wastewater from Berlin.
- In India agricultural wastewater irrigation began in Delhi in 1913 under the supervision of British engineers who introduced this method to Asia. But in Bombay it had begun as early as 1877.
- In Cairo (Egypt) in 1915 urban wastewater was used for agricultural irrigation.[2]

Between the last quarter of the 19th century and the first two decades of the 20th century agricultural irrigation with urban wastewater became a generic method in several countries, both in the centre and also peripherally. Thus, cities became regular water suppliers for irrigation as well as consumers of clean water from other agricultural zones.

10.4 A New Interest in Wastewater Irrigation

In the 1920s and 1930s, agricultural production with wastewater was abandoned by the majority of industrialized countries.

> At the same time, the profiting and recovery were discredited and few engineers or scientists demonstrated any interest in the systematic study of the engineering, agronomical, microbiological and public health aspects by reusing wastewater in agriculture. All of this changed after the Second World War, when a new push towards scientific and engineering interests developed in industrialized countries as well as developing countries (Shuval, 1986: 4).

Three new considerations contributed to this new stage of the developing interest in urban wastewater irrigation.

1. The use of wastewater for irrigation is a good strategy for barren and semi-barren areas, where water resources are scarce and where human and industrial water consumption competes with that of agriculture.
2. Reusing water can be attractive for developing countries, since it economically represents valuable organic supplies that can maintain and improve soil fertility. Theoretically, this situation can decrease the dependency that those countries have on industrialized fertilizers, besides improving their income while cutting production costs.[3]
3. The use of wastewater in agriculture must be carried out with special care in order to limit health risks. It is necessary to establish very strict rules for treating the water being used, as well as for reg-

2 Sources: Shuval (1986); National Academy of Sciences USA (1974); Ríos Brehm (1995).

3 For example, according to a study by Jewell and Seabrook (1979), if all human waste was used from the 638 million inhabitants (population in 1978) in India, their 0.9 million tons of phosphorus and 0.8 million tons of potassium would be enough to cover the demand for chemical fertilizers for its national agriculture. In India irrigation with wastewater is common and an important sanitary risk, as a recent study by Hofstedt (2005) has shown.

ulating harvestable crops (Blumenthal et al., 2003; Hofstedt, 2005).

For an analysis of the comparative effects of these three points the cases of Israel and Chile will be reviewed. Israel presents the condition of an environment that lacks water, in an area where the competition for this liquid acquires a dramatic political dimension, making water availability a national security issue (Shuval/Dweik, 2007). To reduce the pressure on this resource for human consumption, in Israel treated wastewater is used for industrial and agricultural uses, and this requires high quality.

In Israel the state controls the wastewater[4] and its Global Plan for Hydraulic Systems shows an increasing interest in taking advantage of wastewater. In 1982, Israel used 50 million m^3 of wastewater directly for agricultural purposes, 24 per cent of the total 211 million m^3 produced. Of this, 41 per cent is treated rural sewage water and 42 per cent is urban sewage water. In total, around 10,000 hectares of land mainly dedicated to cotton farming (87 per cent), citrus trees (7 per cent), fodder (3 per cent) and crops (1.8 per cent) were irrigated. In 1985, from the total amount of water used for agricultural irrigation, 85 per cent was drinkable and 15 per cent was marginal.[5] The government projection for the year 2000 was that these proportions would be 63 per cent and 37 per cent respectively (Banin, 1993: 173).

Israel's sanitation regulations, which are based on California's, prohibit crop farming with raw wastewater, unless a special permit is granted by the government, certifying that the quality of the water used complies with the legal treatment requirements. While in California and Israel rigorous sanitation controls exist, in the case of using wastewater from the city of Santiago de Chile for agricultural purposes, a severe sanitation problem arose that was resolved in 2007 with the construction of a treatment system.

4 Article 1 of the Israeli Water Laws from 1959 states: "The water resources of the State are public property. The water resources are subject to the control of the State and are intended for the ure of its inhabitants and for the development of the country".

5 They include all sources of water from surface, rain and sewage such as treated wastewater, agricultural sewer water, urban sewers, water originating from floods and salt water.

10.5 The Case of Chile

Israel and the United States, particularly California, are clear examples of new policies for the agricultural use of wastewater, and particularly its treatment before using it in the fields. Both countries have been mindful of the sanitary and safe reuse of water, treating the contaminants before applying them to agriculture. On the contrary, in Latin America, authorities have continued and still continue to propose plans for reusing water that omit the treatment processes prior to using it in the fields, and this agricultural use is considered as a valid way of treating urban wastewater. This is the case in Lima, Peru; in the Valle del Mezquital that is fed by wastewater from Mexico City and used in agriculture; and for many years the wastewater from the city of Santiago de Chile, to name just some of the most representative cases. Considering all of these circumstances, we face a severe sanitation problem, with examples of relatively high mortality rates due to a lack of water quality control and the types of crops that are irrigated.

In the case of Santiago de Chile, the liquid in the water pipes in times of drought consisted of water almost 100 per cent from the current of the Rio Mapocho – the Rio Maipo's tributary is found in Chile's central region. The community of this town generates 850,000 m^3 of wastewater daily; 90 per cent has domestic origins and 10 per cent industrial. At the end of the 1990s, only 4.7 per cent of this waste received treatment of any kind. Water that had not been treated was permitted to flow down the Zanjón de la Aguada, the Rio Mapocho and the Rio Maipo, dispersing 15 m^3 per second.

Roughly 16,000 hectares adjacent to the city were irrigated with this water to produce close to 20,000 tons of crops a year, including lettuce, cabbage, and cauliflower, their main market being in Chile's capital. "This irrigation method of reusing water has caused an important problem with public health, where the region presents increased rates of typhoid fever incidents, which are higher than in the rest of the country" (Ríos Brehm, 1995: 184). According to a United Nations study, the worst problem in the Maipo basin was "irrigating one of the city's most important horticultural producing areas with contaminated wastewater from Gran Santiago, and this is one of the main causes of diseases that affect the community" (NU-CEPAL-PNUMA, 1980: 353, cfr Court Moock et al. 1979).

In a study prepared for the Empresa Metropolitana de Obras Sanitarias (Metropolitan Company for Sanitation Work), results came back stating that the totality of the irrigation canals that were analyzed contained levels of fecal coliforms that were higher than the Irrigation Water Norm. The canals that were most contaminated were those fed by the Zanjón de la Aguada, which, together with the Rio Mapocho, are the main exit route for city drains (CADE-IDEPE, 1990). According to Ríos Brehm, the poor water quality for irrigation in Chile "is fundamentally due to the use of untreated water that comes from rivers and canals that in many cases are the recipients of domestic and industrial contaminants" (Ríos Brehm, 1995: 174). According to this author, all irrigation canals in the Rio Maipo basin rise to above 5,000 to 7,000 times the established norm for fecal coliforms.

A medical investigation in 1974 revealed that 57 per cent of the surveyed population had at one point been infected with salmonella and 30 per cent had developed antibodies against typhoid (Prado, 1974, cited in NU-CEPAL-PNUMA, 1980: 362). In the mid 1970s, between 150 and 200 cases of typhoid appeared every year in the Chilean capital for every 100 inhabitants, and in 1992, rates were recorded between 58.3 and 69.5 cases for every 100,000 inhabitants; this was above the 2.3 registered in Argentina and the 0.2 in the United States, and even above the 20.5 average for South America. The epidemiological studies carried out by the Comité Chileno para la Tifoidea (Chilean Typhoid Committee), from the Chilean Ministerio de Salud (Ministry of Health), concluded that crops irrigated with wastewater from the city were the main vector for the disease (Shuval, 1986: 81–84).

Although the Chilean sanitation legislation contained sanctions for those who used contaminated water to irrigate crops and fruits that were consumed raw, these measures "were not applied until 1991, the year in which a cholera surge was produced in the city" (Ríos Brehm, 1995: 182). This is specifically a grave inconsistency in the state's provisions that according to what specialists say:

> is basically due to the lack of political intent regarding this matter, which is reflected in the lack of economic and human resources (to ensure the fulfilment of the law). A tragicomic example is the application of Resolution No. 350, which is for the irrigation of raw crops from the SSMA (*Servicio de Salud del Medio Ambiente* [Environmental Health Service]). This resolution dates back to 1983 and was not applied until the cholera surge of 1991. On that occasion, crops that had been irrigated with contaminated water in the Maipu zone were burned… Currently, though there may be a suspicion that contaminated water is still used for irrigation, there is no wider investigation (Ríos Brehm, 1995: 182).

This is exactly what happened in the Mexican case of 1991, where after the first few months of governmental alarm over cholera, vigilance disappeared and crops continued to be cultivated with wastewater. Note another similarity between Mexico and Chile: the dispersal of administrative competencies and the duplication of duties.

Currently, the Comisión Nacional de Riego de Chile (National Chilean Irrigation Committee) has started a programme to use treated wastewater in agriculture. For this, a system of treatment plants was constructed to clean wastewater from the capital; the results are yet to be evaluated, although it is known that the use of untreated water for agricultural irrigation has decreased.

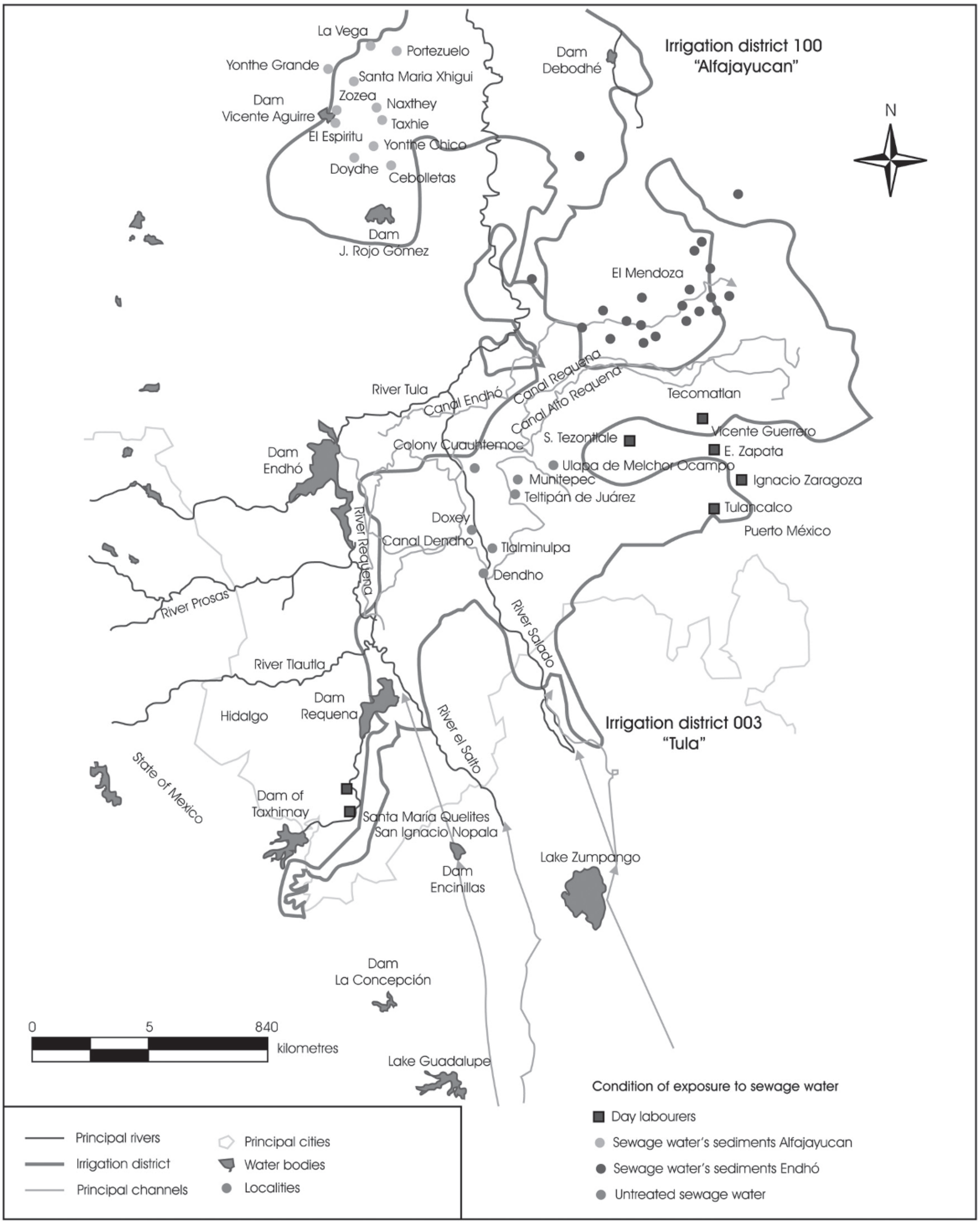
10.6 The Case of the Valle of Mezquital in Mexico

The Valle del Mezquital occupies the south-west and central part of the state of Hidalgo, north-east of Mexico City; it is the furthest south-east border of the vast barren territories that extend through the Mexican north and north-east. The irrigated section is organized into two irrigation districts: 03 and 100. These use a network of main canals and dams, mainly organized around the supply received from discarded water from the metropolitan area of the Federal District.

The last decade of the 19th century is the moment when the relationship between Mexico City and Mezquital was set up as a way of linking wastewater supplies with agricultural use. In part, it is due to the completion of the first tunnel in Tequixquiac that would be more successful than the Tajo de Nochistongo tunnel in artificially opening the basin in the Valle de Mexico and connecting it to the Rio Tula basin. Also, it was the first time the system was designed not to release flooded water accumulated during rainy seasons, but to systematically separate wastewater that came from the city (Musset, 1992: 206). At that time, a regular, permanent and long-term relationship was created. With this, Mezquital became the destination for a permanent flow of wastewater: the liquid that Mexico City discards (figure 10.1).

After the armed movement of 1910, and burdened by the demands of local agricultural groups who were led by corporate leaders of the official party (who at the same time were looking to be accommodated at all levels of the new government), the federal executive branch looked for ways to increase the irrigated

Figure 10.1: Distribution of water for agricultural use in the Valle del Mezquital and types of population exposure. **Source:** CONAGUA (2001: 24).



area, beginning in the 1930s. That role was played out by an agreement signed by President Manuel Ávila Camacho in 1942, where Mezquital was recognized as

> one of the main sources of agricultural product supplies for the capital and republic and... any disposition that increases the production of that district will be reported as a sensitive benefit, as much for the users as for the overall economy of the country (Aboites, 1997).

For that reason, decisions were made to increase the volume of wastewater provided up to 130 m^3 in the low season and 154 m^3 during the rainy season. Due to the growth of the sewerage service in Mexico City, and the increase in water provision for the inhabitants of the capital, it was practically guaranteed that the district would always have available increasing volumes of water for agricultural irrigation. This is a truly privileged situation in relation to all other irrigation districts, since they are always aware of the possibility of losing their water resources, rather than the guarantee of increasing them.

After completing the Tequixquiac tunnel, the construction of the water links between Mexico City and Mezquital began, and with the agreement signed by Ávila Camacho these links were consolidated. The later increases in wastewater volumes received and in irrigated areas developed from a tendency clearly marked in this document. Table 10.1 refers to the documented changes in total irrigation in the Valle del Mezquital with the wastewater from Mexico City:

Table 10.1: Increase in the irrigated surface in the Valle del Mezquital (1931-1990). **Sources:** Bistráin (1961); Aboites (1997); Peña (1997); CEPAL (1991): statistical annex.

Year	Hectare surface	Volume of water in millions of m^3
1931	12,000	238 annual average
1962	25,000	463 annual average
1971	70,000	
1990	90,000	1391

With the construction and start-up of the deep drains, the city's drainage system capacity increased, and this allowed a larger quantity of available water resources to be maintained. The information in table 10.1 allows the increases in wastewater volume entering Mezquital to be compared.

10.7 The Ambiguity of Using Wastewater

Even though at the beginning of the relationship the initiative was taken by the federal government and Mexico City, local participants in Mezquital played a sufficiently active role. From the water concessionaries who constructed the essential parts of the irrigation system (and who continue to be central to the system today), to the farmers who in post-revolutionary times requested water, political alliances were organized and constructed with local leaders to ensure the benefits from a good relationship with the central government that would ensure increasing volumes of wastewater discarded by Mexico City.

Throughout the whole process the relationship appeared to be mutually beneficial. The quality of the water, as wastewater with dissolved organic materials, was also seen positively to increment the crop yield. If the city released the undrinkable water, no one seemed to suffer by it. The city benefited by diverting water that could generate disease amongst its inhabitants, and Mezquital benefited by obtaining a valuable agricultural resource (the large quantity and quality of the fertilizer). The environment also benefited because when passing through different parcels of land, the water would be cleaned, decreasing the contamination of the bodies of water that were the final recipients.

The metropolitan area of the Valle de Mexico operates 27 wastewater treatment plants: 13 in the Federal District and 14 in the State of Mexico. The plants in the Federal District work at 55 per cent of their capacity and half of those in the State of Mexico at 50 per cent of their capacity. Altogether, they only treat 9 per cent of the total wastewater; the remaining 91 per cent leaves the Valle de Mexico without any treatment. Out of all those plants, the one in the Cerro de la Estrella and two from the Lago de Texcoco supply irrigation water within the Valle de Mexico, both after secondary treatment (Academia de la Investigación Científica, 1995: 116–120).

Although there has often been conflict between the agriculturalists and the federal administration about the cost of water, sanitation problems were never the main factor as they were in 1991, when cases of cholera started to be registered in Mexico. During this time, federal authorities dictated strict norms in order to suspend irrigation to all parcels of land in the Mezquital where they thought crops had been growing. This situation threatened the political alliances between the agriculturalist networks, the state, and federal government.

Between July and December of 1991, local, state, and federal authorities had to simultaneously recognize various realities:

a.) In the Valle del Mezquital, crops were being grown with untreated wastewater, a method that was prohibited in almost all countries where wastewater was reused for agriculture.
b.) Although they insisted on pointing out that it was only a relatively small surface that was intended for growing crops that were consumed raw, the

problem increased because the farmers thought it essential for their production strategy.

c.) Broad and detailed judicial guidelines did not exist at that time that would regulate wastewater irrigation in Mexico. Crop farmers were using a risky method for overall health, but it was not illegal. Casting aside hesitation, sanitation authorities – particularly the state manager for the Comisión Nacional del Agua (National Commission of Water, CONAGUA) – began to seize crops that had been harvested illegally, directly at each parcel of land. Punishing behaviour that had been tolerated for a long time was a challenge.

Crop farmers in the Ixmiquilpan area reacted against the government's actions by uniting in different ways and expressing their disapproval of the local arms of the Secretarías de Agricultura y de Salud (Agriculture and Health Ministries). Instead of complying with the government's ban, they organized the Comité en Defensa de las Hortalizas (Crop Defence Committee) and they began resisting the destruction of their crops. The committee brought together all farmers whose crops had been blacklisted, but the leadership was in the hands of small landowners (of 10 hectares or more), who had a stronghold on the regional market and sold their products to neighbouring cities like Pachuca, Mexico, Puebla and Queretaro. After a public struggle, the authorities gave in, due to the fact that the use of wastewater was the cause and product of the political corporate alliances that different federal and state governments had established with the farmers of that region.

Under these conditions, what had once appeared as the best solution for all parties involved resulted in tensions that exploded into the fear that harvesting crops that were irrigated with wastewater would propagate a great cholera epidemic in the 1990s.

The technical advances made throughout the world regarding the relationship between contagious diseases and the use of wastewater in agriculture, the new ways of treating these waters, the importance of guaranteeing good quality for reused water in agriculture, and the role of appropriate judicial regulation over the use of these waters, were all simply ignored by the Mexican authorities as far as agricultural irrigation with urban wastewater in Mezquital was concerned. This is why the farmers in Mezquital reacted with violence to the government's actions in prohibiting the use of wastewater for crop irrigation.

A similar case, although in a smaller area, has been documented and analyzed by Cirelli (2004) on the periphery of San Luis Potosi. In this case, government entities proposed a plan to exchange treated wastewater for subterranean water for use in urban supplies. This deal was supposed to be made with the thermoelectric plant near the municipality of Villa de Reyes. The planners 'overlooked' the fact that the wastewater that was intended for this exchange had come from being used by agriculturalists in Soledad, crop farmers with various products, including some areas that had been banned due to the new sanitation norm. Cirelli demonstrates how the quality of the water in question generated a group of social roles that are generally ignored in other studies about water management.

Returning to the case of Mezquital, apart from the fact that the government of Mexico City had obtained international credit in order to build the treatment plants, the work did not start, even though the site for a large treatment plant had been chosen, in the Valle del Mezquital. One social challenge is that a protest was planned by the agriculturalists from the Valle del Mezquital, since clean wastewater would reduce the amounts they received as well as the amount of organic material that fertilized their parcels of land.

In the case of San Luis Potosi, the current results have been paradoxical: the treatment plant was constructed (Tenorio tank), the agriculturalists accepted an agreement to maintain a secure supply to their crops using part of this water, but the thermoelectric plant – destined for treated water – initially refused to take this water, arguing that their production process could be affected. Part of the treated contaminants continues to be released into crop fields, as was agreed by the company running the purification plant (Dégremont).

10.8 Resistance against Wastewater Treatment: Lessons from the Lerma-Chapala Basin

The slow rate of progress observed in the case of treating wastewater supplied from Mexico City to Mezquital is not atypical. On the contrary, with the exception of some urban areas on the Mexico-US border, a constant high risk can be found facing wastewater treatment in the rest of Mexico. When purification plants are finally constructed, they have already been overtaken by the growing volume of water to be purified, or even worse, they demonstrate severe operational deficiencies and they even stop functioning at an efficient speed. To illustrate this, it is worth reviewing the case of the Lerma-Chapala basin, perhaps the best provided, according to the government. It is not possible to discuss a situation that involves the purification of wastewater for the entire country, and so the case of the Lerma-Chapala basin was selected, given the significant amount of federal investment allotted to it.

Four years before the Consejo de la Cuenca Lerma-Chapala (Lerma-Chapala Basin Council) was formed, the governors of Guanajuato, Jalisco, Mexico, Michoacan and Queretaro signed an agreement with the federal executive branch to move ahead with a programme to treat the basin. The commitment was to build 48 treatment plants for municipal wastewater, with the objective of reducing the contamination of what were considered the 'critical sections': Toluca-Alzate Presa (dam), Salamanca-Rio Turbio and La Piedad-Rio Duero. It was calculated that an investment of 292 million pesos[6] was to benefit the basin and reduce 50 per cent of the Biochemical oxygen demand (BOD) that were circulating within the currents.

In March of 1994, the Basin Council[7] reviewed the results optimistically: 42 plants had been completed and 7 were still in the process of being constructed[8]. The Consultant Council[9] had agreed on a second phase where 52 new plants would be constructed, with a budget of 722 million pesos, more than double the investment of that of the first stage. They also disclosed that they had 38 executive projects that had been terminated within the programme.

In the first phase, the objective was to treat 3,700 litres per second (lps) and in the second phase, 10,950 lps were expected to be treated. Having concluded the programme, 80 per cent of the contaminants in the basin were supposed to have been treated. The expectation was that upon completion in 1994, 48 treatment plants would be operating: 3 in Guanajuato, 5 in Michoacan, 2 in Queretaro, 16 in Jalisco, 20 in the State of Mexico, plus two more plants constructed by the industrial sector, PEMEX and the Comision Federal de Electricidad (Federal Electricity Commission), both in Salamanca. The projected number for the year 2000 was at least 98 treatment plants for municipal wastewater, treating 13,528 lps.

A superficial inventory was taken of the results and it provoked scepticism, not only from what could be seen in the water currents, or from the testimony of agriculturalists, but also from official data.[10] Guanajuato, the state that has the largest part of its territory in the basin, should now have 15 plants in the Lerma basin and be treating 5,690 lps. The results indicate that without even counting the installed capacity of all its treatment plants, it reaches this amount. One of the plants that was finished in the first stage, the one in Abasolo with 70 lps of installed capacity, was still not functioning in 2002.

But, owing to financial reasons, the majority of the plants that were planned for the second stage were built with less capacity, which means that they will soon be saturated with urban waste. The Celaya plant, for example, is working at its maximum capacity, while the one in Salamanca operates at 245 lps, while its capacity is 255 lps. In the case of treatment plants for municipal water, there is a very big difference between the installed capacity and the costs of operation, which may mean that a gap exists while re-collecting and conducting the water of the plant; it is true to say that they are only half-built. On the contrary, when there is a small difference between the installed capacity and the costs of operation, it means that expansion projects must be carried out to provide for the growing demand.

The State of Mexico seems to have performed better in complying with what was promised. The small communities that release into the Lerma River have stabilization lagoons (Almoloya, Atizapán, Atlacomulco and Mexicaltzingo, among others), while Toluca's contaminants, in great amounts and generally more contaminated, pass through one of the two large plants that include sewage sludge. A section of industry has treatment plants exclusively for its own waste.

Jalisco constructed various plants to clean the water that is released directly into Chapala Lake, such as the water from El Chante, San Juan Cosala, Chapala, San Juan Tecomatlan, Poncitlan and Tizapan El Alto, but until now it has not fixed the capital's sanitation system, particularly after a failure with Japanese credit (Boehm/Durán, 1998).

However, the differences between one entity and another could be less if the effective operation of the infrastructure is taken into consideration. A paradigmatic case is that of Michoacan. In Michoacan, the

6 All amounts are given in new pesos.
7 Created on 28 January 1993.
8 One of them from the second stage.
9 Consejo Consultivo de Evaluación y Seguimiento del Programa de Ordenamiento y Saneamiento de la Cuenca (Consultive Council for Assessment & Follow-Up of the Sanitation Regulation Programme of the Basin).

10 See the Inventario nacional de plantas de tratamiento de aguas residuales municipales (Inventory of treatment plants from municipal sewage water).

treatment plant programme has provided limited results, although it is true that most of the plants are found in the Lerma-Chapala basin. In 2004, there were 11 out of 16 treatment plants in the Lerma basin: one in each of the following municipalities: Briseñas, Jiquilpan, Sixto-Verduzco, La Piedad, Quiroga, Sahuayo, Venustiano Carranza, Zacapu and Zamora, and two in Patzcuaro.

Of the five plants that were built in the first stage, three did not function: La Piedad, Sahuayo and Pastor Ortiz. La Piedad was the pride of Michoacan during the first stage. Its special focus was due to the physical and social visibility of the organic contaminants that came from the fishing industry of that area and that were released into the river. Its design consists of two modules with anaerobic and facultative lagoons, with an installed capacity of 200 lps. To perform the purification process, pumping equipment is needed which allows water to travel through the different levels of the system. The pumping equipment has frequently failed and the plant has been non-operational over long periods of time.

The plants in Sahuayo consist of a plant with stabilization lagoons designed to treat 180 lps, which was finished in 1994 and is currently not in use. The third closed plant is the one in Pastor Ortiz, in the municipality of Jose Sixto Verduzco. In the last two cases, the lack of functionality (in those places only), did not prevent 300 hectares of crops from being irrigated with untreated water.

But perhaps the clearest example of resistance found in the treatment of the basin is the delay in the construction of the treatment plant for Morelia, which also appeared in the second phase of the plan discussed above and that could only be completed in 2009; it faces many serious questions about its design and location.

10.9 Conclusions

What has been reviewed here reveals that in the conflict about using untreated wastewater there exists a juncture where politics, health, economy and culture are interrelated. Sufficient evidence is available on the sanitary risk of irrigation with wastewater; this includes direct consumption of these products as well as the danger of the filtration of these contaminants into aqueducts and drinkable water networks. This means that it is pertinent to take regulatory sanitation measures for the use of wastewater, although those dictated by the federal government are incomplete because they only include crop irrigation, brushing to one side the possible contamination of the drinking water consumed in Mezquital or in other areas submitted to the same type of irrigation. What is required is the serious treatment of wastewater from metropolitan sewage given the contamination by industrial waste. Why have the government entities on all levels faced particular difficulties in significantly advancing the sanitation of wastewater for safe use?

All indications show that the model of expansion for the agricultural frontier has collapsed, starting with irrigation with wastewater as the axis of some kind of agricultural growth associated with policies for rural and urban development. It is particularly difficult to modify this situation due to the complexity that surrounds the way in which these irrigation areas were constructed, where the irrigators share collective interests and commitments with those entities that promoted this form of using urban waste.

However, we must call attention to these other points: discarded wastewater has an owner. For this reason, any modification to its use must be made by concluding agreements with the agriculturalists involved to allow for changes that guarantee the new and safe use of this water. Wastewater treatment must be carried out by sharing the costs between all parties involved. It is neither realistic nor just to assume that these costs can be transferred to the agricultural sector, which has already suffered.

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11 Effects of Land Use in the Hydrology of Montane Catchments in Central-eastern Mexico

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11.1 Introduction[1, 2]

The La Antigua river upper watershed (1,325 km^2), located on the eastern slopes of the Cofre de Perote-Pico de Orizaba volcano (central Veracruz, Mexico), is a region of high biodiversity and great hydrological importance. The watershed plays a key role supplying water to main urban areas, such as the capital of Veracruz (Xalapa) and Coatepec, and providing downstream water for agricultural purposes and local fisheries, among others. The *tropical montane cloud forest* (TMCF) is a high value ecosystem because of the hydrological services it provides. Although many of the forests in this region have been disturbed or converted to crops and grasslands (112 km^2) in the last 30 years, the hydrological effects of these changes at the catchment scale are still largely unknown, particularly in the case of the Mexican TMCF. This chapter addresses this knowledge gap by studying three headwater catchments (<50 ha) covered with, respectively, old-growth TMCF, 20-year old regenerating TMCF, and pasture, with the following objectives: 1) to evaluate the hydrological effects of TMCF disturbance and its conversion to pasture, with emphasis on annual and seasonal distribution of streamflow (baseflow and stormflow), and 2) to determine the effects of land use on stream-suspended solids exportation. The study period covered two years (2005–2007) during which continuous rainfall and streamflow data were collected. The results showed a higher stormflow (run-off produced by rainfall) in the regenerating forest and pasture (4.5 and 6.2 per cent of the rainfall, respectively) as compared with the old-growth forest (2.2 per cent), most likely because of a combination of lower canopy water interception and reduced soil infiltration. Nevertheless, the stormflow values observed across the different land cover types were very low (<6 per cent of rainfall) as a result of the very high infiltration capacity of the volcanic soil. The bedrock characteristics underlying the catchments appeared to be a key factor controlling their annual streamflow, particularly the baseflow. The pasture stream showed the highest concentrations of total suspended solids (10 mg l-1) compared with the forests (3.2 mg l-1), presumably due to higher surface run-off causing soil erosion. It is concluded that the TMCF disturbance and conversion to pasture modifies the eco-hydrological functioning of the catchments. However, the results also suggest that 20 years of natural regeneration following cloud forest disturbance in eastern Mexico is capable of producing near-original hydrological behaviour.

Land use change can influence hydrology, shifting the water fluxes between precipitation, evapotranspiration and streamflow (Li et al., 2007). Forest conversion to pasture or agricultural lands can modify the hydrological cycles of catchments by increasing or decreasing their water yield, or even diminishing stream baseflow levels during the dry season in the short term (Croke et al., 2004; Bruijnzeel 1990, 2004). In the long term, the reduction of evapotranspiration and therefore the decrease of water recycling into the atmosphere may lead to a reduction of regional precipitation (Savenije, 1995; D'Almeida et al., 2006). In addition, land use change can induce alterations in pH, electrical conductivity, temperature, and solute

1 We thank the Municipality of Coatepec, Veracruz, and the inhabitants of Loma Alta, Coatepec and Cocoxatla, Xico, Veracruz for permitting us to work on their land properties. The research work was supported by CONACYT (Grant No. 149367, 43082). Additional funds were provided by MSc Griselda Benítez (Grant No. 10093) and phD Miguel Equihua (Grant No. 10024) from the Instituto de Ecología, A.C., Xalapa, Ver., Mexico, which are gratefully acknowledged.
2 Keywords: montane forest, regeneration, pasture, stream flow, catchments, Veracruz.

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and nutrient concentrations in the streams (Nunes et al., 2003) that may affect biogeochemical processes and stream ecology.

Most of the hydrological studies in humid tropical catchments have been focused on evaluating the streamflow changes of (selective) logging of old-growth forests (Chappell et al., 2005) and the plantation-harvesting hydrology of forests (Bruijnzeel, 2004). However, much less information is available on the hydrological changes of forest disturbance and conversion to pasture in tropical regions.

The tropical montane cloud forest (TMCF, known as 'bosque mesófilo de montaña' (Rzedowski, 1996). is a highly valuable ecosystem in Mexico and in other countries around the world (Aldrich et al., 2000). This is because its ecological functionality has resulted in a number of environmental services that provide benefits to the human population, i.e. a clean and stable water supply (Maass, 2003). Despite their hydrological importance, many of these forests have been disturbed or converted to other land uses. Hence, TMCF registers one of the highest deforestation rates among tropical forests (1.1 per cent; Doumenge et al., 1995, Aldrich et al., 2000). TMCF occupies between 0.5 per cent and 1 per cent of Mexico's surface area (Rzedowski, 1996). In the central part of Veracruz state (central-eastern Mexico), 26 per cent of the old-growth and secondary TMCF has been converted to crop and pasture lands during the last 30 years (112 of 427 km^2; Muñoz Villers/López Blanco, 2007). Consequently, most of the TMCF has been reduced to fragments occupying ~10 per cent of their original area (Williams-Linera et al., 2010). Currently, it is a highly endangered ecosystem in the region (Williams-Linera et al., 2002). TMCF depletion in the region was associated with a much greater deforestation process in Mexico which reached its highest level at the beginning of 2000. The deforestation rates placed Mexico as one of the five countries with the highest loss of forests and woodlands around the world. Fortunately, this situation has raised the awareness of the population and led to different national and regional conservation programmes (i.e. 'Cruzada por los bosques y el agua' of SEMARNAT; Fondo Forestal Mexicano from CONAFOR, and the Payments for Environmental Services Program of INE-CONAFOR; Manson, 2004). Perhaps the best-known example of the *Payments for Environmental Services* (PES) scheme in Mexico is the case of the municipality of Coatepec, Veracruz, which launched the PES programme for the first time in 2002, with the purpose of protecting the TMCF uplands in recognition of the value of TMCFs as local providers of high-quality water.

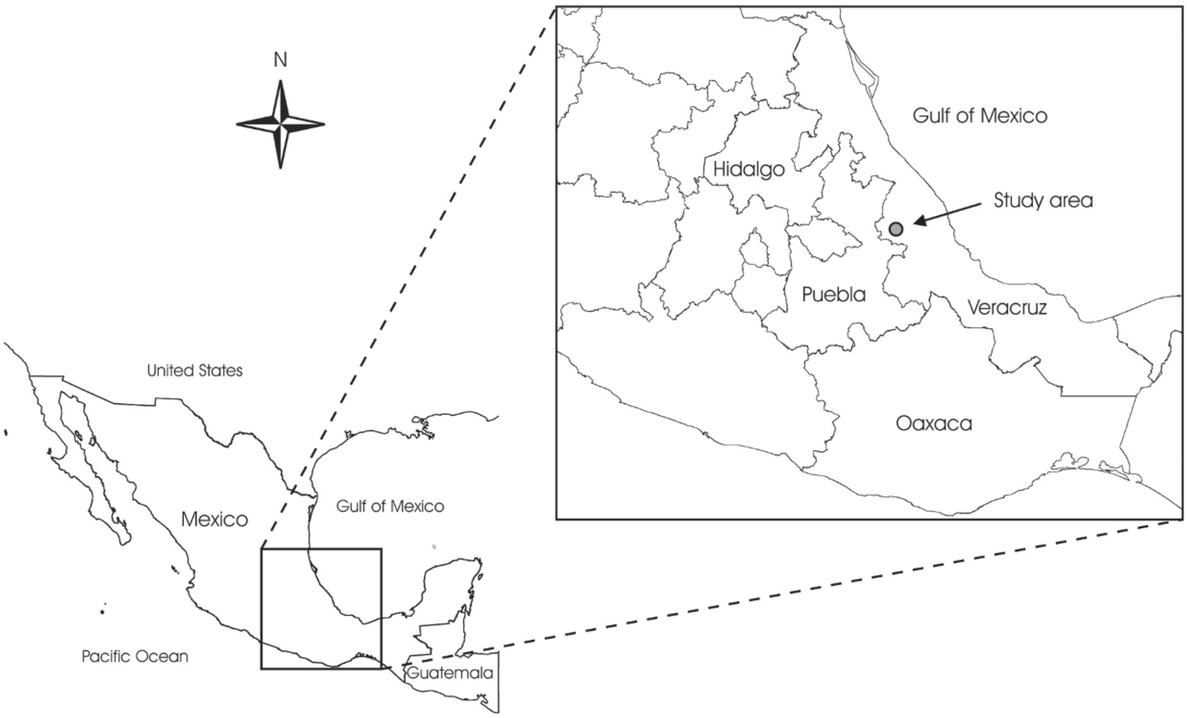
Scientific knowledge about the hydrological effects of TMCF disturbance and conversion into other land uses is very scarce. The lack of information is mainly associated with the topographic and climatic complexity of the landscape, since hydrometeorological measurements are difficult to obtain in remote and mountainous regions (Bandyopadhyay et al., 1997). Currently, the available information comes from research work performed in the TMCF of Asia and Central and South America. Hence, the hydrological functioning of the tropical montane forest ecosystems in Mexico is virtually unknown.

This chapter will quantify and evaluate TMCF disturbance and conversion to pasture effects on streamflow dynamics and suspended solids exportation in a seasonally dry TMCF setting in central Veracruz state (central-eastern Mexico), using continuous and high-resolution field measurements over a two-year period. The research questions of the investigation were: 1) How is the seasonal and annual streamflow modified by TMCF disturbance and its conversion to pasture at the scale of the catchment? 2) How does the run-off produced by rainfall compare between land cover types? and 3) How does the change in land use alters the total suspended solids exportation in the streams?

11.2 Study Area

The investigated catchments are located in the La Antigua river upper catchment (1,325 km^2), on the eastern slopes of the Cofre de Perote volcano (central Veracruz; figure 11.1). The climate is temperate humid with abundant rains during the summer (Köppen classification modified by Garcia, 1988). Climate can be divided into three seasons: a rainy season (May–October), a cold-dry season, influenced by cold fronts, the so-called 'Nortes' (November–February), and a dry-warm season (March–April). Mean annual rainfall and temperature is 2,500 mm and 18°C, respectively. The old-growth and regenerating cloud forest catchment (henceforth called MAT and SEC; 25 and 12 ha, respectively) are located within the 'La Cortadura' Ecological Reserve, Coatepec, Veracruz (97°02'W and 19°29'N; ~2.100 m above sea level). The pasture catchment (PAS; 35 ha) was located in Cocoxatla, Xico, Veracruz (97°02'W and 19°23'N; ~1,600 m above sea level; Muñoz Villers, 2008). The streams draining the catchments are perennial. The soils were classified as Andosols of volcanic origin. The soils in

Figure 11.1: The Study Area. **Source:** Muñoz Villers/López Blanco, 2007. Ancillary data from INEGI (1993; Scale 1: 250,000).



the forest catchments are developed on a permeable, moderately weathered limestone breccia, which in turn are underlain by weathered and fractured basaltic andesite rock from the Oligocene-Neogene period (D. Geissert, personal communication), whereas the pasture catchment is underlain by highly weathered limestone breccias over impermeable lava layers (Geissert et al., 1994).

The MAT forest is a well-conserved, old-growth montane cloud forest, with an average canopy height of about 27 m, and emergent trees up to 40 m (García-Franco et al., 2008). The dominant tree species were *Miconia glaberrima, Clethra macrophylla, Parathesis melanosticta, Oreopanax xalapensis* and *Quercus ocoteifolia*. The SEC forest is a 20-year old regenerating TMCF. By secondary succession processes, the most abundant species are *Miconia glaberrima, Alnus jorullensis, Prunus tetradenia, Quercus corrugata* and *Clethra macrophylla*. The PAS catchment is covered by grassland used extensively for dairy cattle practices established more than 40 years ago. The dominant grass species is *Paspalum notatum* with some scattered trees of *Liquidambar styraciflua* and *Acacia sp*. (Muñoz Villers, 2008).

11.3 Materials and Methods

11.3.1 Precipitation

From 1 August 2005 to 31 July 2007, precipitation (*P*) was measured in the study catchments using tipping-bucket rain gauges, placed in open areas and at about 0.3 m from the ground. Detailed information about the equipment and sampling network can be found in Muñoz Villers (2008). The data from the tipping-bucket rain gauges were verified by weekly readings from standard rain gauges (totalizers) placed at a distance of about 1 m from the automatic ones. The totalizer rain gauges consisted of a 100 cm^2 funnel and a 25 cm high PVC pipe. The totalizers were read using 100–1000 ml graduated cylinders, depending on the rainfall volumes accumulated.

Precipitation totals were calculated on an event basis and as the average value of the volumes measured by each rain gauge located in the respective catchments. Precipitation inputs consisted exclusively of rainfall, i.e. inputs by fog were not considered, since the amounts involved were very small (50 mm; 2 per cent of the annual rainfall; Holwerda et al., 2007, 2010). Further, rainfall time series were re-sampled at different time intervals for subsequent analysis.

11.3.2 Streamflow

From 1 August 2005 to 31 July 2007, streamflow (*Q*) was measured at the MAT and PAS, and the SEC catchment outlets using 90° and 53.8° V-notch weirs, respectively. Water levels were recorded every 2-min using Schlumberger LT F15/M5 divers in combination with F5/M1.5 baro-divers to compensate for atmospheric pressure (both having ± 1.5 mm accuracy). Water levels were read from a staff gauge every 2 weeks to verify the diver measurements. Water levels were converted to *Q* (l s-1) using the experimental stage-discharge relationships for the weir (Kindsvater/Carter, 1957), calibrated with field volumetric and salt dilution measurements of discharge (Muñoz Villers, 2008; for further details).

11.3.3 Soil Physical Properties and Infiltration Capacity

Soil profile descriptions were carried out at the top, mid and bottom slope positions on both sides of each catchment. To determine soil bulk density, undisturbed soil samples were collected using 5 x 5 cm stainless steel rings (volume 100 cm^3) at each soil profile and various depths. As well as this, the cylinder method was used to determine the apparent density (ρ_b). The samples were weighed using an analytical balance (Sartorius CP124S), and oven-dried at 105 ºC for 48 hours. Bulk density was calculated as the ratio of the mass of the oven-dry sample to its bulk volume. Total porosity was calculated as the ratio between apparent and real density of each sample. The real density was determined using a pycnometer (50 ml; Brand, Germany) previously calibrated according to NOM-021-RECNAT 2000 (SEMARNAT, 2002).

11.3.4 Sampling and Determination of Suspended Solids in the Streams

Three water samples were collected monthly at each catchment outlet from August 2005 to August 2006. Due to logistic difficulties associated with the remoteness and inaccessibility of the catchments studied, the stream water samplings could only be carried out during baseflow conditions and not during stormflow (run-off produced by rainfall events). The water samples were collected in 940 ml polyethylene bottles, and kept refrigerated at 4 ºC for less than 48 hours in the laboratory of the Functional Ecology Department, Institute of Ecology, AC-Xalapa, Veracruz. Next, the water samples were filtered through a glass fibre Whatman GF/C filter (1.2 μm) using a Nalgene filtering device of 1000 ml. Each filter had been previously dried at 105 ºC for 24 hours and weighed on a Sartorius BP 211D analytical balance. After the filtration the filter underwent the same procedure. The quantification of the concentrations of the total suspended solids (TSS) in mg l-1 was obtained through the difference between the filter weights before and after filtration (Horwitz, 1980).

11.3.5 Baseflow and Quickflow Separation Analysis

A rainfall event was defined as precipitation that was preceded by a dry period without rainfall for at least 3 hours (Schellekens et al., 2000; Bruijnzeel, 2006; Cuartas et al., 2007). All the rainfall-run-off events (hydrographs) that occurred during the study period were analysed. For rainfall events of less than 10 mm, a detailed analysis was carried out to identify those that generated quickflow or stormflow (run-off generated per rainfall event), using as a criterion an increase of more than 1l sec-1 in the streamflow. The separation of streamflow (*Q*) into baseflow (*Qb*) and quickflow (*Qd*) was performed according to Hewlett and Hibbert (1967).

11.3.6 Run-off Coefficient Determination

Qd represents a fraction of the precipitation. This fraction is called *run-off coefficient* (*RC*), and it is used as an indicator of the infiltration and storage processes (Scherrer, 1997) of the catchments. This fraction is also known as response factor (Hewlett/Hibbert, 1967), and it is expressed dimensionlessly as

$$RC = \frac{Qd}{P} \quad (1)$$

where *Qd* represents quickflow, and *P* refers to precipitation. Values are expressed in mm.

11.3.7 Statistical Analysis

The set of observed or transformed data (logarithm) was compared to investigate significant differences between the land cover types (treatments). The normality of the data was investigated using the Kolmogorov-Smirnoff statistical method (Chakravart et al., 1967). The homogeneity of variance of the samples was examined through the Levene statistic. The one-way ANOVA method with *post hoc* comparison of means (Tukey procedure) was used. When the assumption of normality and equality variances of samples was not justified, the non-parametric Kruskal-Wallis method (Kruskal/Wallis, 1952) was used for multiple comparisons through the median and Mann-Whitney tests. The confidence level at which the statistical tests were performed was 0.05.

11.4 Results and Discussion

11.4.1 Precipitation

During the study period, the mean annual *P* was 2,939 and 2,962 mm in the MAT and SEC, respectively, and 2,857 mm in PAS. On average, 270 rainfall events per year occurred between August 2005 and July 2007. Even though the sites were located at different elevations (forests and pasture at 2,170 and 1,500 m above sea level, respectively), only small differences were found in their total annual rainfall inputs. The precipitation showed a clear seasonal pattern. 77 per cent of the annual *P* occurred during the rainy season (May–October), while the dry-cold season (November–February) and the dry-warm (March–April) contributed 16 per cent and 7 per cent respectively (figures 11.2a, 11.2b). During the wet season, precipitation events were derived primarily from orographic-convective precipitations (high intensity and short duration), while the stratiform precipitation (low intensity and longer duration) characterized the dry season events. The average rainfall intensities documented during the rainy season (2.73, 3.08, 3.74 mm hr-1; MAT, SEC and PAS) compare well with the average rainfall intensities reported in Luquillo, Puerto Rico (3 mm hr-1; Schellekens et al., 2000), but they are slightly higher than those observed in Monteverde, Costa Rica (1.81 mm hr-1; Clark et al., 1998).

The frequency distribution of the rainfall events showed a strong skew to the left (not symmetric). The median rainfall and intensity event values were 4.5 mm and 1.60 mm hr-I for the forest catchments, and 5 mm and 1.99 mm hr-I for the pasture, respectively, markedly lower than the mean values (figures 11.2a, 11.2b). Hence, 51 per cent of the rainfall events were characterized by light rains (≤ 5 mm), but they only contributed 7 per cent and 9 per cent to the total annual rainfall in the forests and pasture catchments respectively.

11.4.2 Soil Physical Properties

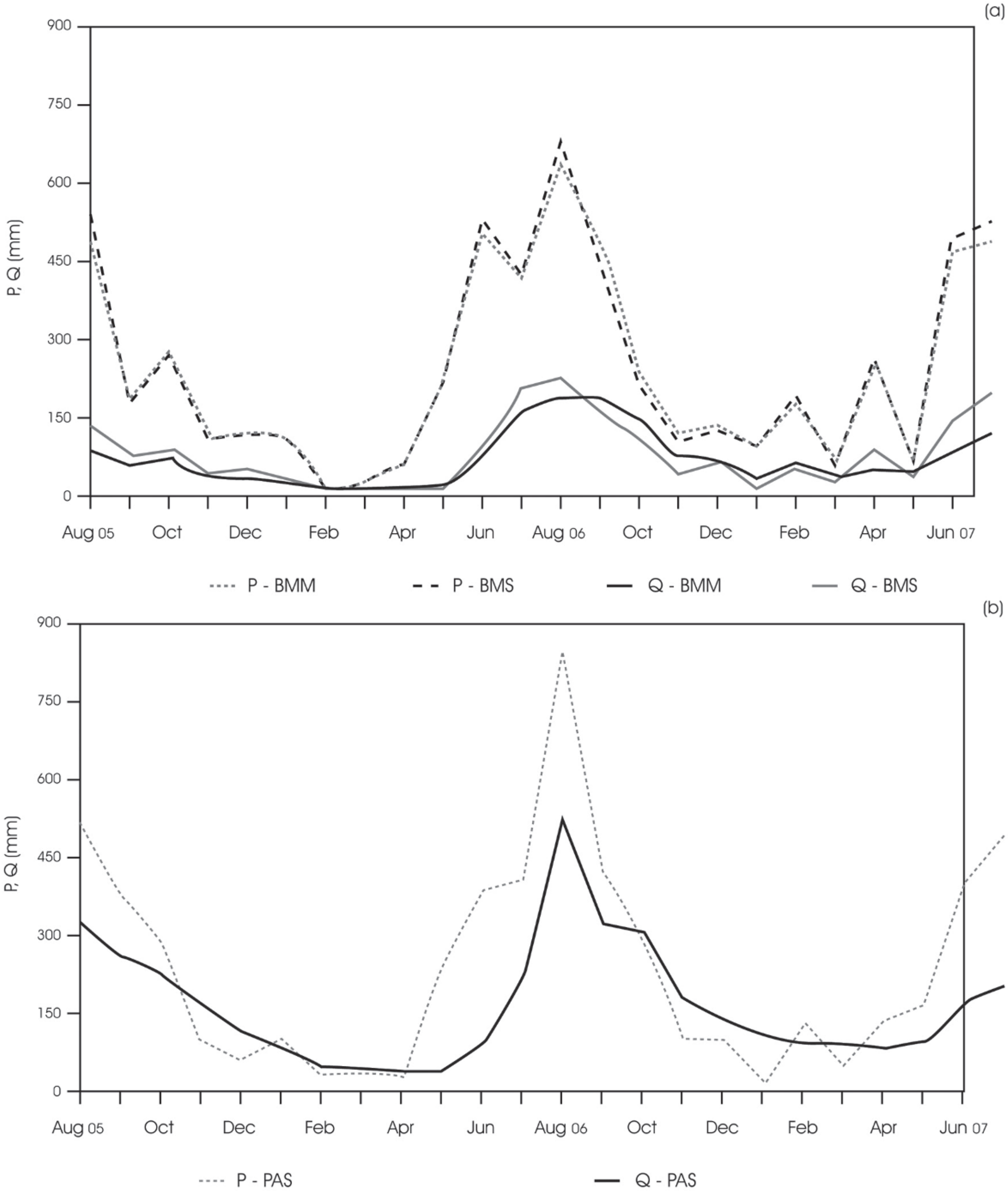
The soils under forests showed low bulk densities (0.41 g cm-3; mean value) and high porosities (0.77; mean value) compared with the pasture (0.64 g cm-3, 0.67, respectively). However, the differences found between the forests and pasture were small and could indicate a well-conserved soil structure in the latter (Meza, personal communication). According to Geris (2007), the soils in the pasture catchment showed greater compaction and less infiltration capacity in the topsoil than the forests (292, 190 and 100 mm hr-1: MAT, SEC and PAS, respectively). This may lead to a higher occurrence of surface run-off and soil erosion in pasture compared with forests.

11.4.3 Streamflow

The mean annual *Q* was 859 and 995 mm for MAT and SEC, respectively, and 1,967 mm for PAS during 2005–2007. Streamflow clearly followed the seasonal variability of the rainfall (figures 11.2a, b). *Q* generated during the wet season was about 74 per cent, 76 per cent and 71 per cent in the MAT, SEC and PAS, respectively. The rainy season showed the highest mean and maximum daily and monthly *Q* values, whereas the dry season reported the minimum *Q* values (table 11.1). MAT showed the lowest annual (859 mm) and mean daily *Q* values (1.38 mm; data not shown) over the study period. However, MAT and SEC were very closed in their annual and mean daily seasonal streamflow amounts (table 11.1). In contrast, PAS showed the highest annual (1,967 mm) and mean daily *Q* values (4.7 mm) which were approximately twice and three times as much, respectively, as those from the forests.

Expressed as a percentage of the corresponding *P*, *Q* was 28 per cent, 33 per cent and 68 per cent for MAT, SEC, and PAS, respectively, where baseflow (Q_b) accounted for most of the total *Q* in the catchments studied (84–91 per cent of *Q*). The small differences found in the *Q/P* fractions of MAT and SEC (5 per cent), are mainly attributed to the lower canopy interception of the secondary forest. Comparing the *Q/P* fractions of MAT and SEC with those found in other humid tropical montane catchments shows that they are lower than the values derived for a lower montane rain forest in Puerto Rico (34 per cent; Bisley II catchment, Schellekens et al., 2000), and for a tropical montane cloud forest in Monteverde, Costa Rica (39 per cent; Bruijnzeel, 2006). This is probably due to differences in climate conditions (rainfall characteristics; intensity and duration of the rainfall

Figure 11.2: Monthly rainfall and streamflow distribution in the mature and secondary montane cloud forests, and (b) in the pasture catchments. **Source**: Muñoz Villers (2008).



events), and geological (permeable, impermeable bedrock) and physiographic factors (size, shape and aspect of the catchment slope lengths, among others) between sites.

The greater *Q/P* fraction obtained in PAS is primarily attributed to its lower water use (F. Holwerda, data unpublished) and its bedrock characteristics (thick and impermeable lava layer) compared with the forests (permeable and fracture breccia); the latter can be an important factor in determining baseflow levels in catchments underlain volcanic substrates (Bruijnzeel, 2004). In this case, the difference in the bedrock nature of the catchments investigated was linked to their spatial location in the Cofre de Perote mon-

Table 11.1: Annual totals of streamflow (*Q*) plus monthly mean, daily mean, minimum, and maximum *Q* (± standard deviation) for the wet, "Nortes" and dry seasons as measured at the mature (MAT) and secondary (SEC) cloud forests and pasture (PAS) in central Veracruz, Mexico, from Aug. 1, 2005 to Jul. 31, 2007. **Source**: Muñoz Villers (2008).

Sites	Season	Q	Qmonthly	Qmean	Qmin	Qmax
MAT	Wet	638	105 ± 55	2.52 ± 1.4	1.48 ± 0.9	5.62 ± 2.3
	"Nortes"	173	43 ± 22	1.15 ± 0.7	0.73 ± 0.2	1.81 ± 1.1
	Dry	56	28 ± 15	0.49 ± 0.2	0.51 ± 0.2	0.93 ± 0.3
	Total	859				
SEC	Wet	755	126 ± 66	3.28 ± 2.9	1.33 ± 0.8	10.97 ± 6.1
	"Nortes"	166	41 ± 16	1.16 ± 0.8	0.61 ± 0.3	2.81 ± 1.2
	Dry	75	38 ± 38	0.47 ± 0.2	0.36 ± 0.2	1.54 ± 0.5
	Total	995				
PAS	Wet	1391	232 ± 131	8.53 ± 6.4	5.16 ± 2.5	23.0 ± 5.9
	"Nortes"	454	114 ± 43	3.78 ± 1.4	3.00 ± 1.2	5.28 ± 1.7
	Dry	123	61 ± 28	1.77 ± 0.8	1.5 ± 0.8	2.34 ± 0.9
	Total	1967				

tane (pasture catchment was located at the mid slope ~1,500 m above sea level, whereas the forests were located at mid-upper slope ~2,100 m), so they differ in origin, formation and geomorphological processes (Meza, Geissert, personal communication).

11.4.4 Run-off Response to Rainfall

Continuous measurements of *P* and *Q* at high resolution (10 min) over a 2-year period allowed us to evaluate and quantify the streamflow response (quickflow; *Qd*) to rainfall. Total *Qd* corresponding to annual *P* was 2 per cent (76 mm) and 5 per cent (185 mm) for MAT and SEC, respectively, and 8 per cent (319 mm) for PAS. These results showed a higher stormflow in SEC (109 mm year-I) and PAS (243 mm year-I) compared with MAT, although the difference across land use covers was found to be very small. The low rainfall-run-off event ratios obtained in the three land use catchments are mainly attributed to the high porosities and high infiltration capacities of the volcanic soils (Andosols; Tobón et al., 2010). Also, the mean rainfall depths and intensities prevailing in this region are considered low (~10 mm and 2–5 mm hr-I, respectively). Thus, the occurrence of rainfall events that exceed the soil infiltration rates is also low. Contrasting the *Qd/P* ratios obtained in MAT (2 per cent) and SEC (5 per cent) with other tropical montane forests, the values found in the present study are similar to the 3–5 per cent obtained for an evergreen montane forest in southern Tanzania (Bonell, 2005), but low compared with the 9 per cent derived for a lower montane rain forest in Puerto Rico (Schellekens et al., 2000). In regard to pastures, there is very little information available for tropical regions, with the exception of the work carried out by Germer et al., (2009), who obtained a *Qd/P* fraction of 22 per cent for a pasture catchment in Rondonia (south-western Brazilian Amazon).

11.4.5 Rainfall-run-off Event Analysis

On an event basis, run-off coefficient values (*RC*; *Qd/P*) showed a non-normal distribution. Statistical analysis suggested significant differences between land cover catchments ($\chi 2 = 20.49$, $p \leq 0.0001$). The observed non-Gaussian distribution of the *RC* values is in line with results derived from studies performed at plot and catchment scale (Descheemaker et al., 2006; Merz et al., 2006). Multiple comparison analysis showed that *RC* values in MAT were significantly different from SEC ($p = 0.024$) and PAS ($p \leq 0.0001$) (table 11.2). The *RC* values of SEC only suggested differences from PAS ($p = 0.026$). Table 11.2 shows that the *RC* values obtained for SEC and PAS were nearly double and triple the values of MAT, respectively. However, the *RC* values derived were generally low across land use types. Figure 11.3 shows box plots of *RC* fractions for the three investigated catchments. As can be seen, PAS showed the highest *RC* fractions and the largest variation, whereas MAT showed the lowest. Some of the maximum *RC* fractions (outliers) ob-

Figure 11.3: Runoff event coefficient values (*RC*) for each studied catchment. **Source**: Muñoz Villers (2008).

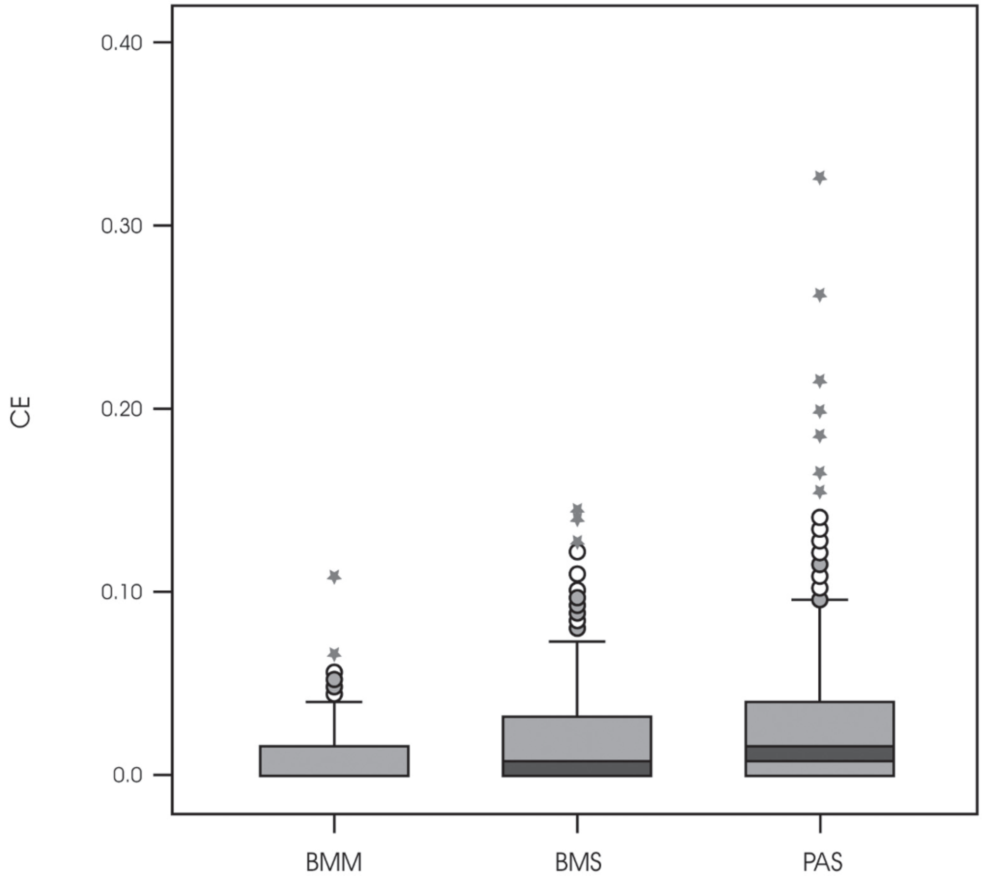


Table 11.2: Runoff coefficient (*RC*) statistics for the mature (MAT) and secondary (SEC) cloud forests and pasture (PAS) in central Veracruz. **Source**: The authors.

Sites	N	Mean	ED	Min	Max	Absolute values		
						25	50 (median)	75
MAT	292	0.010	0.014	0.00	0.108	0.000	0.003[A]	0.015
SEC	293	0.018	0.028	0.00	0.143	0.000	0.004[B]	0.030
PAS	312	0.028	0.045	0.00	0.326	0.000	0.010[C]	0.038

tained for the three catchments correspond to run-off responses to extreme rainfall events occurring in the 2005 and 2006 wet seasons (May–October), such as the Tropical Storm Jose (August 2005), Hurricane Stan (October 2005) and some tropical thunderstorms (July 2006).

11.4.6 Total Suspended Solids (TSS)

MAT and SEC showed similar TSS concentrations; statistical differences were only suggested between SEC and PAS ($F = 4.2$, $p = 0.022$). PAS registered the highest mean concentrations of *total suspended solids* (TSS) compared with forests (table 11.3). This is mainly explained by its lower soil infiltration capacities leading to a greater exportation of solids via storm run-off in the pasture compared with the forests during the rainy seasons. The results obtained in this study agree with the findings of Neil et al. (2001) and Thomas et al. (2004) in the Brazilian Amazon, and also with those derived from Ramos-Escobedo (1998) and Vázquez and Ramos-Escobedo (2008) in Veracruz, Mexico.

Table 11.3: TSS stream water mean concentrations (mg l-1 ± standard error) for the investigated catchments. The superscript letters indicate significant differences between land cover types ($p < 0.05$). N = 12. **Source**: The authors.

	MAT	SEC	PAS
TSS	3.8(1.2) ^{A}	2.6(1.1) ^{A,B}	10.0(4.5) ^{A,C}

11.5 Conclusions

Rainfall (*P*) and streamflow (*Q*) were measured continuously at high resolution in an old-growth and a 20-year old regenerating montane cloud forest and pasture catchments in central Veracruz, Mexico, over a 2-year period (August 2005–July 2007). The field hydrometric measurements were used to evaluate the annual and seasonal streamflow, and run-off in response to rainfall events between the different land cover types. Monthly stream water samplings were carried out to determine total suspended solids exportation in the stream catchments. The main findings of the present study are summarized as follows:

- Tropical montane cloud forest disturbance and conversion to pasture generated higher total streamflow amounts. For the secondary forest, this was primarily associated with its lower water canopy interception, and for the pasture with its lower water use and reduction of soil infiltration compared with the old-growth forest. Run-off in response to rainfall (stormflow) was lower in the mature forest. However, the rainfall-run-off ratios obtained for the different land use catchments were generally low due to the prevailing climatic conditions of the region (small rainfall events and low rainfall intensities) in combination with the high infiltration rates of the volcanic soils (Andosols).
- The bedrock characteristics underlying the catchments were a key factor determining their total annual streamflow amounts, consisting mostly of baseflow. In this case, the pasture catchment showed the greatest baseflow levels due to its less impermeable parental material (thick lava layer) compared with the forests (permeable and fracture rotten breccias).
- The pasture stream showed the greater concentrations of total suspended solids, presumably due to a higher occurrence of surface run-off, thereby greater surface soil erosion and the mobilization of particulate matter into its stream compared with the forests.
- Although the pasture catchment registered the lowest soil infiltration capacities, its water yield during the dry period was similar, and even somewhat higher than, those from the forests. Possible reasons for these results are: 1) lower water use (evapotranspiration) during the dry season compared with forests (Holwerda, data not published); 2) well-conserved soil physical properties due to low indications of land degradation; and 3) the lithological nature and weathering processes of the pasture catchment promotes the formation of clayey soils characterized by their higher soil water retention properties.

The cloud forest disturbance modifies the eco-hydrological functioning of catchments. In this case, the old-growth and secondary forest catchments showed very similar seasonal and annual streamflow characteristics, and also stream suspended solids concentrations. This could suggest that 20 years of natural regeneration after disturbance was sufficient to largely restore the original hydrology.

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12 Impact of Land Use Changes in the Surface Hydrodynamics of a Water-harvesting Basin

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12.1 Introduction[1, 2]

Watershed management requires systematic measurements in order to reach good resources control. Some processes conditioning water transfers in the environment such as rain, run-off, infiltration, deep percolation, water uptake by plants, and evapotranspiration should be quantified to improve our knowledge of hydrological characterization and of the best management practices (Descroix/Nouvelot, 1997; Descroix et al., 2004). This work presents infiltration measurements and results produced with the Suction Disc Infiltrometer method realized in the Upper Nazas River Basin. This basin is the main water supply for Irrigation District 017 in northern Mexico, called the Lagunera region. Results show that soil surface controls the hydrodynamic behaviour of the watershed. Land use changes can be linked with productive practices that are causing strong hydrological consequences.

Watershed management is a priority issue in many regions of the world especially in arid and semi-arid lands where water is the main limiting factor for production and economic development (Sanchez, 2005; Loyer, 1998). Since the late 20th century, the organization of watershed councils for major rivers in Mexico has pursued the integrated management of water basins as part of the effort to solve the complex set of water problems: supply, quality, sanitation and cost, raised from several production sectors and user types: agriculture, livestock, industrial and urban public (Gonzalez Barrios et al., 2007).

Water is a key resource and driver of economic development for many regions in Mexico; and it is an element whose presence depends on the conditions of the natural environment, but also on the influence of productive activity. Therefore, managing water basins requires a good knowledge of the natural and productive systems that use water or have a decisive influence on water quality. Watershed parameterization is therefore a matter of prime importance as a source of information.

After a brief introduction to the study area, this chapter will present the materials and methods used as well as the results and their implications for the upper Nazas River basin and for its dependent cropping area.

12.2 Study Area

The research was conducted in a catchment located in the Upper Nazas River Basin (figure 12.1). The 'Cienega de la Vaca' watershed is located in the mountain range of the Sierra de la Candela that conforms to the Sierra Madre Occidental in the northern state of Durango (SEMARNAT, 2007) and includes parts of the municipalities of Guanacevi, Santa Maria del Oro and Tepehuanes (figure 12.2). The Sierra de la Candela has an approximate area of 1200 km^2 and its altitude ranges from 2,500 to 3,200 metres above sea level. Its shape is quite elongated from north to south with a landform characterized by hilly slopes. The main geological components are rhyolite-ignimbrite, as in most of the western Sierra Madre (Descroix et al., 2001).

The hydrological network of the Sierra de la Candela is formed by two main tributaries of the Sixtin-El Oro River flowing northward and then south-eastward; and the Tepehuanes (flowing north to south) – Santiago (south to north, in the same *graben*), called

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2 Key words: watershed management, infiltration, hydrological cycle.

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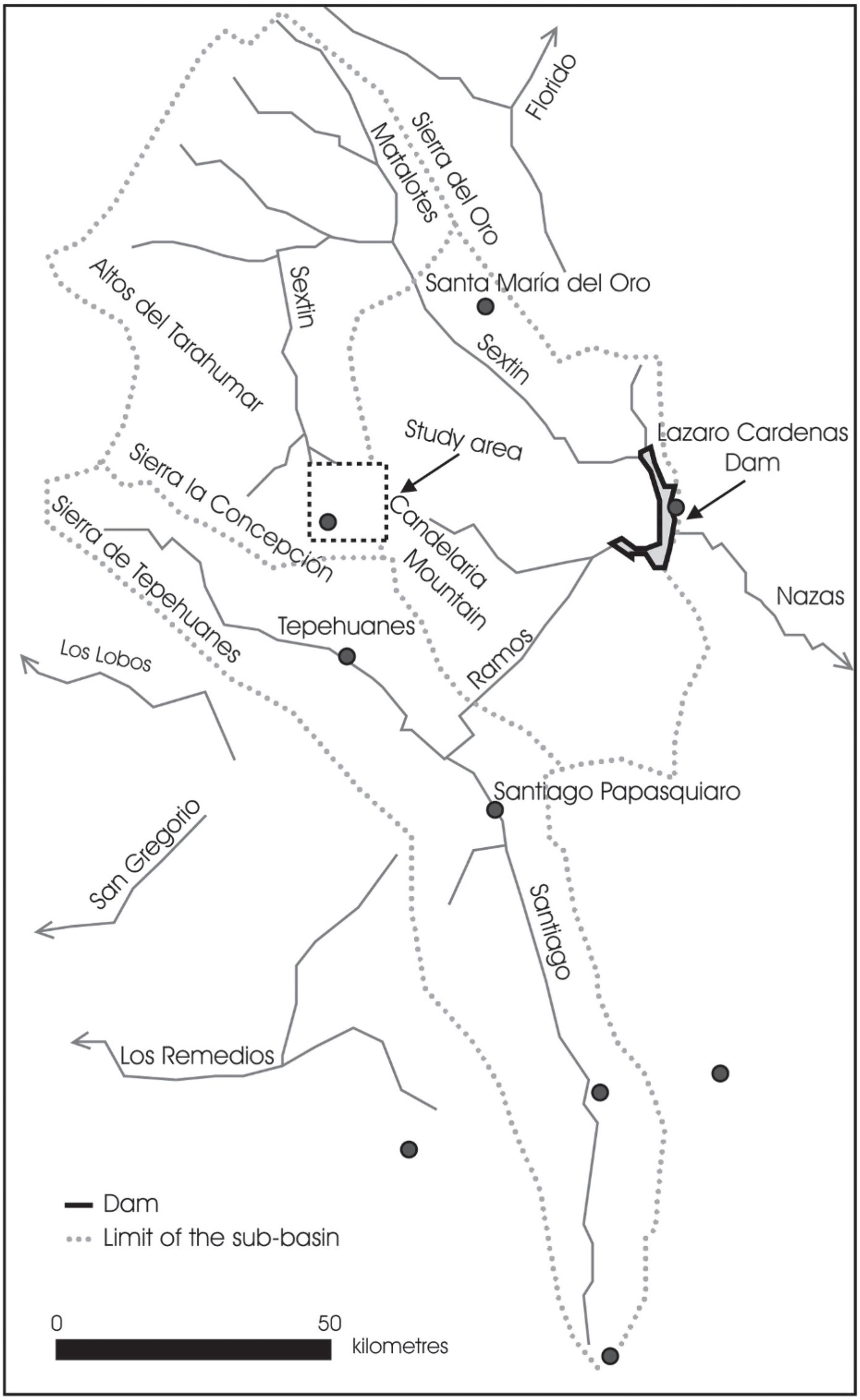
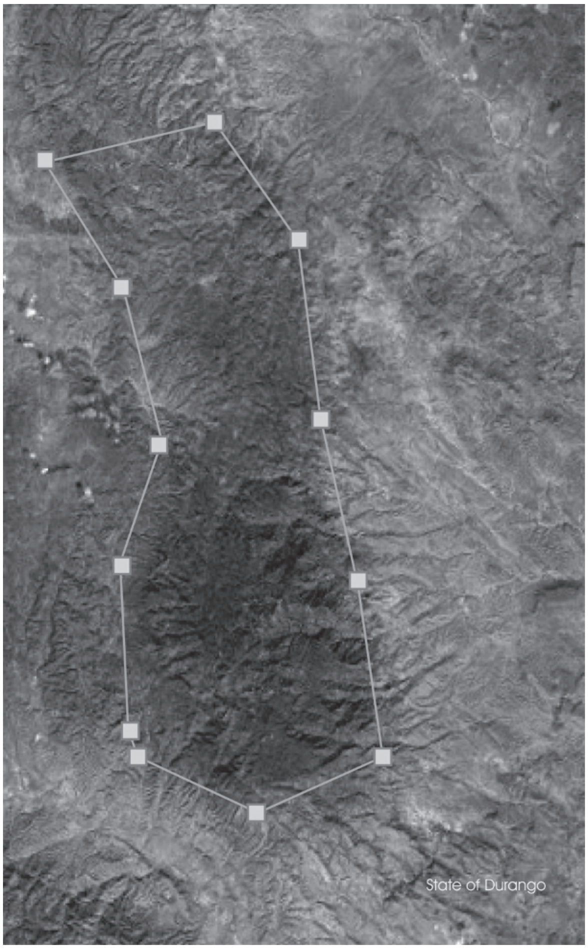
Figure 12.1: Location of the Upper Nazas River Basin. **Source:** Authors' research data.



Ramos River after their junction. Both (the Ramos and Sixtin rivers) meet at the Lazaro Cardenas reservoir (Descroix, 1995). The predominant run-off process is of the Hortonian type (Horton et al., 1933; Descroix et al., 2002) but under certain conditions of soil capacity for water storage a subsurface run-off or Hewlettian-Cappusian type was observed, consisting of contributory water-saturated zones (Cappus, 1960, Hewlett et al., 1969).

Figure 12.2: Sierra de la Candela. **Source:** Image from Google Earth in the public domain.



In the Sierra de la Candela, some important forest resources remain, especially pine and oak forests that have been used since the mid-20th century in different patterns and locations, but generally over-exploited (Rodriguez, 1997; Descroix et al., 1998). Wood is carried to the main sawmills of Parral, Chihuahua, Santiago Papasquiaro and Durango (Viramontes et al., 2004). This forest plays a crucial role for the hydrological and environmental services offered by the Sierra de la Candela in terms of water capture and transfer, since it receives an annual average of 840 million cubic meters of rainwater, given an average rainfall of 700 mm over its total area.

The ‘Cienega de la Vaca’ watershed occupies 18 km^2 approximately in the highest part of the Sierra de la Candela (2,700 to 3,180 meters above sea level). This watershed belongs to the ‘Ejido Peña y su anexo El Salto’ in the municipality of Santa Maria del Oro Durango, whose productive activities are forestry and livestock. The predominant vegetation in the watershed is pine and oak forest on Cambisol type soils (FAO, 1998), many of which have mulch consisting of both deciduous species (oak) and conifers (pines). In the valleys of the basin there are grazing areas on slightly deeper soils (Gonzalez Barrios et al., 2000).

12.3 Methods

Four sites were chosen as representative of the main surface features present on the watershed. Infiltration test were made on each one of them. These selected surfaces are pine mulch, oak mulch, grass and bare soil (degraded by cattle trampling). The Suction Disc Infiltrometer method proposed by Vandervaere (1995) and Perroux & White (1988) was employed to measure the infiltration capacity at a constant controlled load (figure 12.3) with three different radio discs (4, 10 and 12.5 cm) and four pressure head values planted in the soil (-100, -60, -30 and -10mm). For each measurement point other complementary parameters were determined with classical laboratory methods (Plenecassagne et al., 1997). These parameters are soil texture, bulk density, water content and initial soil moisture at field capacity. All these data allow the characterization and quantification of soil hydraulic conductivity depending on the surface features (figures 12.4 to 12.8).

At least three tests were carried out on each type of soil surface, applying different suction values from -100 mm to -10 mm (table 12.1).

Table 12.1: Number of infiltration tests conducted in each type of surface. **Source:** Authors’ research data.

Soil surface:	N total	N (disc of 12.5 cm)	N (disc of 10 cm)	N (disc of 4 cm)
Pine mulch	19	7	6	6
Oak mulch	3	0	2	1
Grass	26	8	11	7
Trampled bare soil	7	0	0	7

12.4 Results

The infiltration tests conducted in the main types of soil surfaces of the watershed reveal large spatial variability of hydraulic conductivity in the soils. Sensitive

Figure 12.3: Suction Disc Infiltrometer. **Source:** Vandervaere (1995).

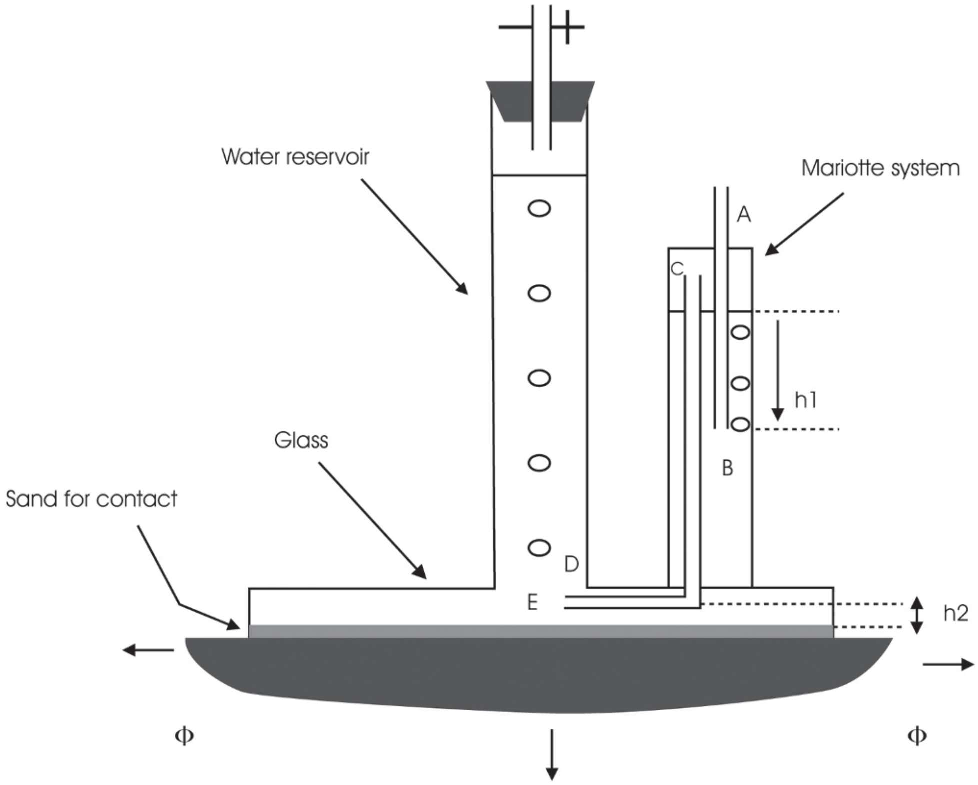


Figure 12.4: Surface of pine mulch. **Source:** Photo from research taken by members of the team.

differences are observed between the unstructured porous medium on bare soils degraded by cattle trampling and the well-structured porous medium on pine or oak mulch surfaces. The grassland areas have an intermediate behaviour.

Figure 12.5: Surface of oak mulch. **Source:** Photo from research taken by members of the team.

Figure 12.6: Surface of grass. **Source:** Photo from research taken by members of the team.

Figures 12.8, 12.9 and 12.10 show the results of infiltration tests on three different surfaces. In all figures the water flow is greatly reduced during the first few seconds, then it fluctuates a moment in order to stabilize. This stabilization can be interpreted as a steady state having been reached. Then the suction applied by the

Figure 12.7: Surface of bare soil degraded by cattle trampling. **Source:** Photo from research taken by members of the team.

Mariotte system is changed to a lower value, and the flow increases and becomes stable after a certain time. The operation is repeated for different suctions at -100, -60, -30 and -10 mm. Although in most cases the flow increases with decreasing suction applied, there are exceptions, particularly for tests carried out with the large disc (12.5 cm) in the pine mulch surface (figure 12.9).

The infiltration flux is not stabilized at a suction of -100 mm and does not increase when the value of suction is changed, but sometimes the flow increases a long time after the suction. After observing this relationship, the suction rate was deliberately increased to show whether the flow decreased to the previous value observed. It was found that the values of flow at the suction of -30 mm are quite similar to those observed during the initial test phase, although the applied suction of -60 mm and -100mm is smaller (hysteresis phenomenon).

When applying a -10 mm suction in this test (figure 12.10) the phenomenon of soil surface wetting can be described as follows: at the beginning of the test the soil surface is dry: the system behaves as hydrophobic; it becomes hydraulic-conductive after more than 4 hours, while the angle of the surface water meniscus in contact with the solid surfaces becomes smaller, allowing more water to infiltrate. Subsequent flow analyses with decreasing suction and later increasing suction shows that this effect is irreversible and that it may be linked to the organic nature of the mulch components.

In physical terms, the hydraulic conductivity K is not constant when the medium is not saturated, but varies with water content θ (or pressure head h). When moisture decreases, a decrease in hydraulic conductivity is observed. The relationship between the hydraulic conductivity and the pressure head K (h) depends very strongly on soil texture. Under saturation conditions ($h \geq 0$), K takes the highest value, called saturation hydraulic conductivity Ks.

Because ($h < 0$) in unsaturated conditions, and K varies depending on h, we can use the following exponential relationship to describe this change (Gardner, 1958):

$$K(h) = Ks \exp(\alpha h) \quad (1)$$

where α is a parameter characteristic of soil texture.

Using the method of Ankeny et al. (1991) and Reynolds/Eldrick (1991), the soil hydraulic conductivity can be obtained depending on the suction applied, and the saturation hydraulic conductivity (Ks) deduced as well as the average value of α using the pressure head intervals applied (from -100 mm to -10 mm) fitting the experimental data (presented in figures 12.8, 12.9 and 12.10) to the exponential relationship between hydraulic conductivity and suction of equation (1). The results of this calculation are presented in table 12.2.

Table 12.2: Values of Ks and α calculated for three soil surfaces. **Source:** Research data-

Surface type:	Ks (mm/h)	α (mm^{-1})	$α_{sat}$ (mm^{-1})
Pine mulch	60.84	0.070	0.017
Grass	46.44	0.021	0.047
Bare soil degraded by trampling	54.72	0.048	0.050

The calculation with equation (1) implies that α is constant in the range 0 to -100 mm, but in reality this parameter is linked to a hydraulically functional pore size and can vary depending on the applied suction. It follows that the $α_{sat}$ value corresponds to α value with a suction of 0 mm which is obtained by extrapolation according to the following empirical relationship,

$$α(h) = α_{sat}\exp(βh) \quad (2)$$

where β is a fitting parameter.

According to capillary theory (White/Sully, 1987) we can get an idea of the size of hydraulically functional pore size with the next equation,

$$λ_m = \frac{σα}{ρ_w g} \quad (3)$$

where σ is the surface tension (0.073 Newton/meter in standard conditions).

The pore size calculation using equation 3 gives the results presented in table 12.3.

Table 12.3: Functional pore size λm calculated from equation 3. **Source:** Research data.

Surface type	Average pore size (μm) unsaturated conditions. Suction from -100 to -10mm	Pore size (μm) saturated conditions. Suction = 0mm
Pine mulch	521	1281
Grass	156	349
Bare soil degraded by trampling	358	372

The difference between the two pore sizes reflects how soil porosity is structured. In a well-structured soil, the size of functional hydraulic pore varies depending on suction and water-saturated conditions. According to table 12.3 the functional pore size is similar under both conditions for the bare surface. This surface as studied lacks an organized structure for its functional porosity (inter-connectivity between pores of different size), which would be expected in a surface disturbed by cattle trampling. The grass surface is less homogeneous than the bare one, and shows a difference in functional pore size between the two conditions (figure 12.10). This site has better structure and connectivity within the pore network. The surface with pine mulch shows a very structured porous system with a large difference in functional pore size range but with a hydrophobic behaviour that may create a delay in infiltration efficiency.

In each one of the studied surfaces, hydrodynamics will be different and cause different hydrologic impacts downstream. The consequences of uncontrolled production systems such as ranching and forest harvesting can have consequences at the basin scale in terms of infiltration run-off and erosion according to that observed in other parts of the Nazas River Basin by Poulenard (1995; 1996), Gomez (1997), Perez (1998) Descroix et al, (2000), and in terms of quantity and quality of water harvested by the watershed.

These results highlight the importance of soil surface features and measurement of infiltration properties in the service of decision-makers in the management of water transfer basins. It is therefore necessary to measure these parameters in areas where there is no information in order to provide relevant and reliable management recommendations.

12.5 Conclusions

The soil surface features are very important in the processes explaining the hydrodynamics of the basin; they often reflect the way the soil and vegetation are managed in the watershed. The consequences of uncontrolled production systems such as ranching and forest harvesting can be significant at the basin scale in terms of infiltration, run-off and erosion as well as in terms of quantity and quality of harvested water.

Watershed management for water production requires a good knowledge of reliable and robust parameters in order to propose a convenient management of water resources. Given the lack of information, the experimental studies of hydrology and soil science

Figure 12.8: Infiltration tests on bare surface degraded by cattle trampling. **Source:** Authors' research data.

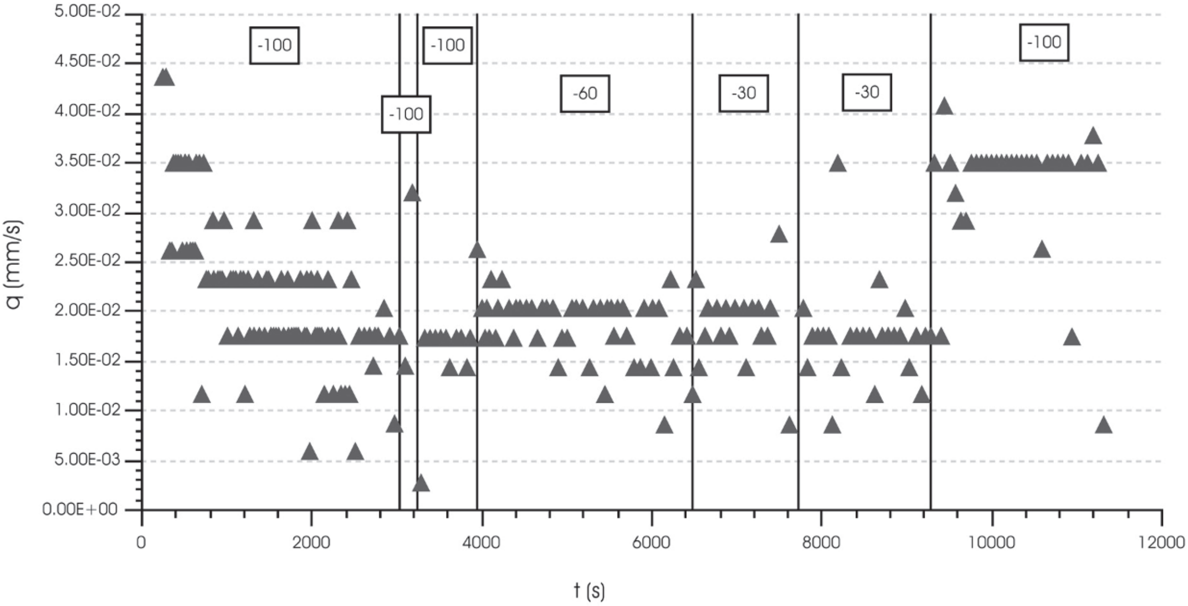
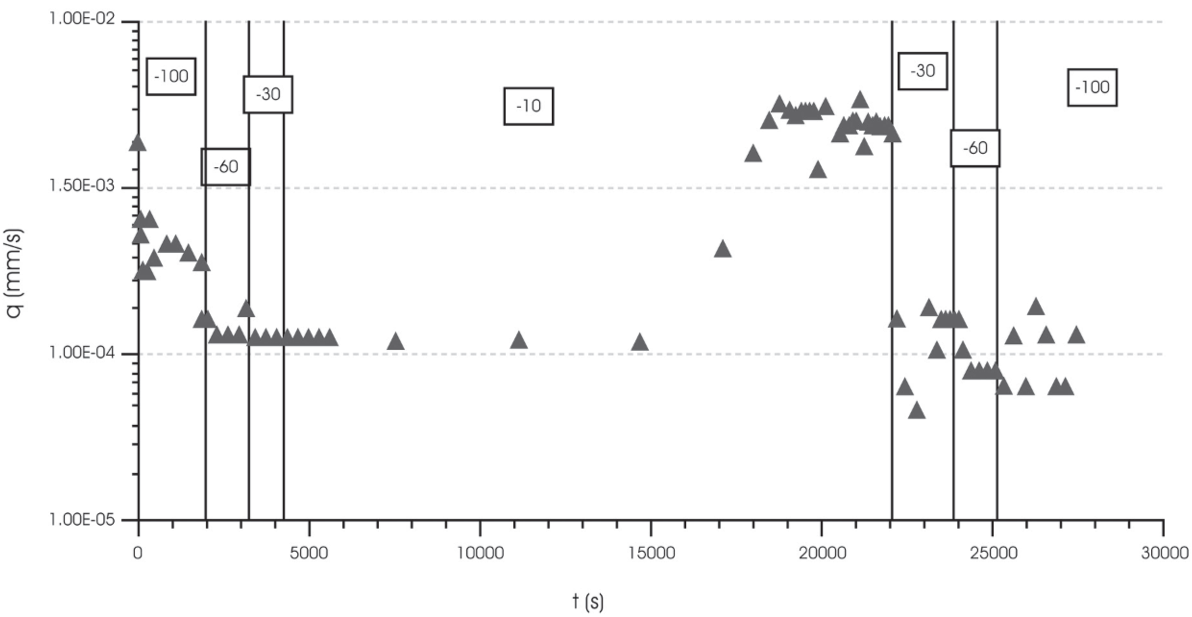


Figure 12.9: Infiltration tests on surface with pine mulch. **Source:** Authors' research data.

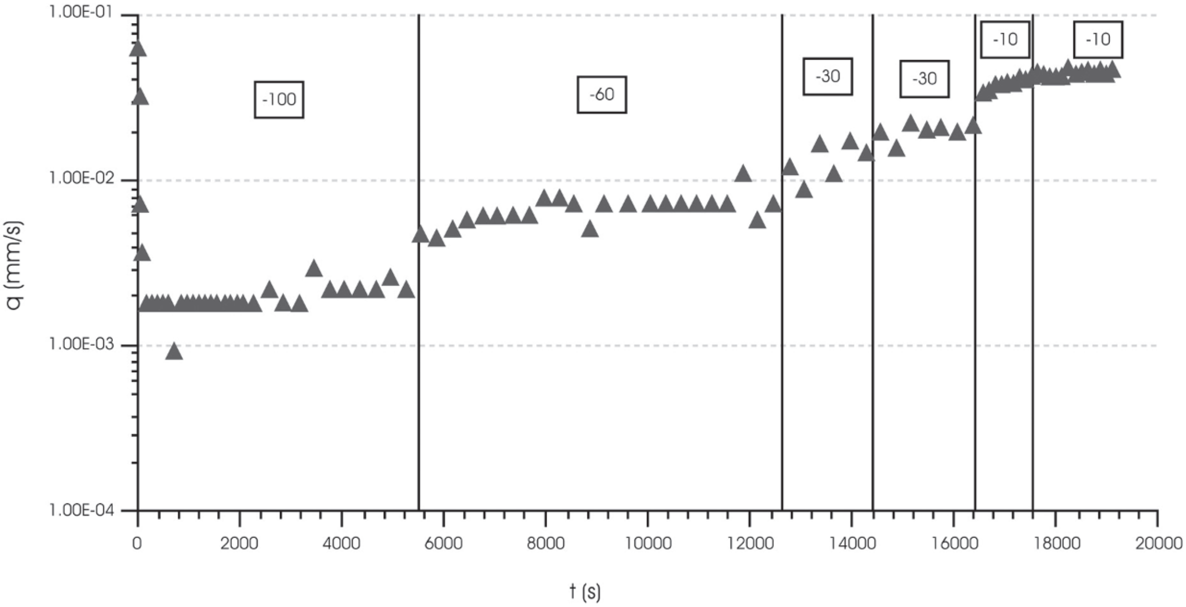


are useful in order to improve understanding and to reliably quantify the hydrological functioning of water-harvesting basins such as that presented in this paper.

The Upper Nazas River Basin is the main source of water supply for agriculture in Irrigation District 017 in Northern Mexico, which has suffered decades of land use changes linked to strong pressure from forestry production, agriculture and livestock. Limited infiltration, accelerated run-off and heavy erosion are some of the hydrological impacts which modify the quantity and the quality of the stream flow of the basin.

The results of this work on experimental infiltration illustrate the importance of limiting production activities in accordance with potential hydrological impacts of the observed features in order to improve soil and water management and to perpetuate water harvesting for the areas that depend on the water supply of the Upper Nazas River Basin.

Figure 12.10: Infiltration tests on grass surface. **Source:** Authors' research data.



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13 Evapotranspiration in the Upper and Middle Nazas River Basins

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José Luis González Barrios and Alejandro López Dzul

13.1 Introduction

Evapotranspiration, a combination of two simultaneous physical processes which account for the loss of water in vegetation-covered soils, through water evaporation from the moist soil-vegetation surface and control of transpiration through specialized plant tissues (stomata), is a fundamental hydrological variable at regional and basin levels for decision-making aimed at improving the water planning and management demanded by farming activities so as to maximize its usefulness, especially in arid and semi-arid zones where water resources are scarce or uncertain (Pereira et al., 2006; Dinpashoh, 2006; Jacobs et al., 2008). Also, evapotranspiration is an important time and space describer for climate regime classification, especially when related to precipitation. This variable is also a major soil-water balance component (Arora, 2002; Mundo/Martínez, 2002).

The need to know evapotranspiration for various applications has encouraged the development of methods and instruments for measuring and estimating evapotranspiration at a relatively short timescale: millimetres per day (mm d^{-1}), and even shorter intervals (mm h^{-1}). Direct measurement of actual evapotranspiration is usually determined through weighing lysimeters and the gravimetric method. Other high-precision methods to determine actual *evapotranspiration* (ET) are energy balance and turbulent correlation (Eddy correlation). However, due to their high economic cost and the need for fairly large-sized plots, weighing lysimeters and turbulent correlation methods are only used with the purpose of generating new methods, and for testing and adjusting existing models (López et al., 1991; Jiyane/Zermeño, 2003; Sammis et al., 2004).

In 1975 the *Food and Agriculture Organization* (FAO) of the United Nations proposed that the term "reference evapotranspiration" (ET_0) be used to describe a reference crop's (grass or alfalfa) water demand as a climate condition effect which, integrated with a series of crop and soil factors, is used to estimate *ET* (Doorenbos/Pruitt, 1975; Jensen et al., 1990; Smith, 1991), to the extent that nowadays there are numerous empirical and semi-empirical equations which may be used, although most of them require previous calibration in order to define their usefulness at a local level (López et al., 1991; Pérez J. P./Castellví, 2002; López et al., 2006). Among these semi-empirical mathematical models, the one developed by Penman-Monteith (Penman-Monteith FAO, 1956) is widely used to estimate ET_0 and subsequently manage irrigation, due to the fact that it has been widely accepted by the world scientific community and has been proposed by the FAO as the standard method for calculating ET_0 from climate information (Allen et al., 1998; Allen et al., 2005).

Direct *ET* and ET_0 measurements have been made in very few sites in Mexico because, unfortunately, there are only about three lysimeters installed and working (Ojeda, 1999; Villaman et al., 2001). Meanwhile, direct field determination by means of turbulent correlation has recently been used more frequently in very detailed studies (Moguel et al., 2001; Jiyane/Zermeño, 2003). On the other hand, other work designed to improve irrigation water planning and use – based on *ET* as a variable to be measured in daily periods for soil-water balance modelling – have been reported by Mundo and Martínez (2002) for Irrigation District 05 (Delicias, Chihuahua) and by Ojeda (1999) for Irrigation District 075 (El Fuerte, Sinaloa). With these, it has become possible to achieve savings of up to 30 per cent of water per surface unit with field-validated parameters (Sifuentes et al., 1999).

Further important work has been reported by Catalán et al. (2007); however, unlike the other work mentioned, this proposes a computer program to calculate water demand in various irrigation districts of Mexico, based on *ET* obtained from historical climate data. In accordance with these, as of 2005 the *Na-*

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Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_13,

tional Centre for Disciplinary Research on Water-Soil-Plant-Atmosphere Relationships (CENID RASPA, INIFAP) installed a climate monitoring system by telemetering land linking three autonomous weather stations in a network. Such stations are located at different sites in the Nazas River basin, with the purpose of monitoring the weather environment and having information available for various applications, among which has been the determination of *ET* as the main variable for describing climatology and irrigation water management: in the short term, for the pecan crop (6,375 ha) and, later on, for forage crops (in the case of alfalfa, 31,739 ha).

For describing the climatology of particular zones, the CENID RASPA network is evidently insufficient, both because of its size and because of the time it has been operating, since an observational analysis of over 30 years is required. Therefore, this can only be achieved with weather data recorded by conventional weather stations (e.g. the National Meteorological Service stations), although these are inconvenient because of the limited availability of observed weather variables, and it is in this sense that the interest of the CENID RASPA network lies. Based on the above, the object of this chapter is to estimate reference evapotranspiration (ET_0) in two sub-basins of the Nazas River from standard weather data, using the Penman-Monteith FAO, the Doorenbos-Pruitt, and the Hargreaves-Samani mathematical (1985) models, and to compare them with the data observed in the A-type tank.

13.2 The Nazas River Basin

The Nazas River basin is a hydrologic region with 36 main watersheds, located in north-central Mexico at a latitude of 23° to 27° N and a longitude of 106° to 102° W (figure 13.1). This watershed comprises 71,906 km^2 in surface area, and 95 per cent of the water resources produced there are used for agricultural production (mainly for crop irrigation), a highly controversial issue as the water resource is nowadays being excessively exploited.

Researchers from CENID RASPA of INIFAP, in collaboration with the French *Institute of Scientific Research for Development in Cooperation* (ORSTOM), currently known as the IRD (*Institut de Recherche du Développement*), conducted studies which have allowed us to demarcate the Nazas basin into three main sub-regions, based on annual precipitation analysis using the regional vector method, and also based on major component analysis, with precipitation being the dependent variable and altitude, longitude, and vegetation density as independent variables (Decroix et al., 1997; Decroix et al., 2004). These sub-regions are as follows:

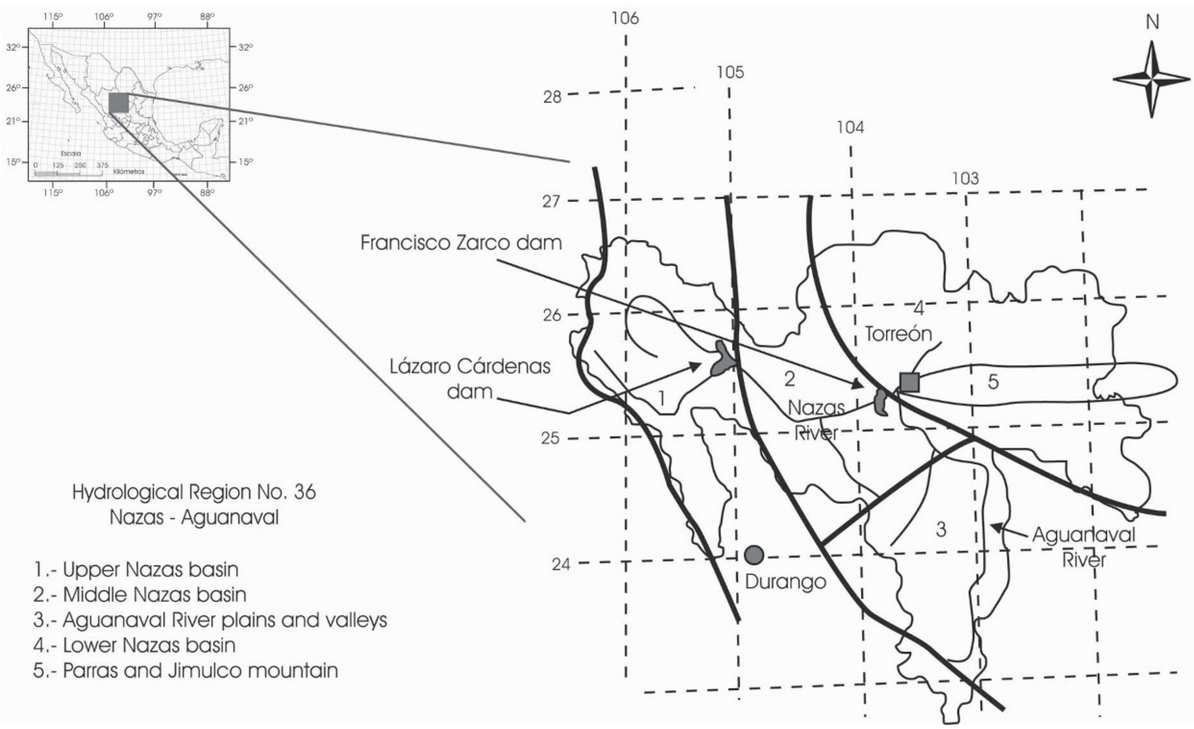
- The *Upper basin* starts in the Western Sierra Madre mountains in the state of Durango, and is classified as a sub-humid water-producing and -storing zone (this is where the Lázaro Cárdenas dam is located and obtains its water supply), with the highest vegetation indexes and over 500 mm average annual precipitation, generating 85 per cent of all run-off.
- The *Middle basin*, with a 300 to 500 mm mean annual precipitation generates only 15 per cent of all run-off and is considered as a semi-arid water storage, conveyance and resource management zone (this is where the Francisco Zarco dam is located) towards the lower Nazas River basin. Its limits may be defined as lying between the Francisco Zarco and the Lázaro Cárdenas dams.
- The *Lower basin* is located beyond the Francisco Zarco dam, downstream to the Mayrán Lake, with under 300 mm average annual precipitation. It is classified as an arid zone with water consumption for agricultural production from the upper and middle basins and water extraction from deep wells. Naturally, it is in this sub-basin that the water problem is at its greatest, with serious water management issues, excessive exploitation of aquifers, and accelerated diminishment of water quality.

Given the above, it is necessary to complete the characterization of the sub-regions with climate information. Therefore, the instrumentation of the basin is very convenient with respect to hydro-climatic applications (dry spells and their impact on the environment and on agricultural production) as well as to agro-climatic applications (water availability, demand, planning and management for agricultural activity, application of water saving technologies for irrigation, and crop selection, in the case of the lower basin).

13.3 Materials and Methods

Autonomous weather stations were the instruments used to monitor the climate for estimating ET_0; these stations were distributed as follows (figure 13.2). Two weather stations were installed in the lower basin: a Davis station, in standard reference crop conditions,

Figure 13.1: Nazas River Basin. **Source:** Adapted from Decroix et al. (2004).



and a Motorola station, the condition of which remains non-standard and therefore is not analyzed in this chapter. The first is located at the geographic coordinates: 25º35’18.090’’N, 103º27’01.523’’W, and 1129 m (CENID RASPA), while the second is at 25º37’02.136’’N, 103º24’11.952’’W, and 1126 m (at P.P. Las Villas, in Torreón, Coahuila). An Adcon station was installed in the middle basin and for standard reference crop conditions, at 25º14’43.928’’N, 104º07’06.230’’W, and 1243 m (P.P. Santa Bárbara, Nazas, Durango).

The Davis and Adcon stations are equipped with electronic sensors of the same brand, and the Motorola station has Decagon ECJ20 sensors. These sensors measure air temperature, atmospheric moisture, wind speed and direction, solar radiation, and precipitation at 2 metres above ground surface, and another sensor measures soil temperature at a 30 cm depth. All stations were programmed to record climate variables in one-minute periods and to consider the average of 15 recordings, i.e. every 15 minutes, to be stored in a database pertaining to each station. Subsequently, the information was requested through a computer program connecting the stations in a telemetering network, via radio frequency and at 15-minute intervals in the case of the Davis and Motorola stations, while the Adcon station data were obtained via modem, at twenty-four hour intervals. This computing system, which permits real-time monitoring, storage, use, and observation of climate variables occurring at each study site, was developed and installed in a central computer located at the CENID RASPA facilities (Ochoa, 2006).

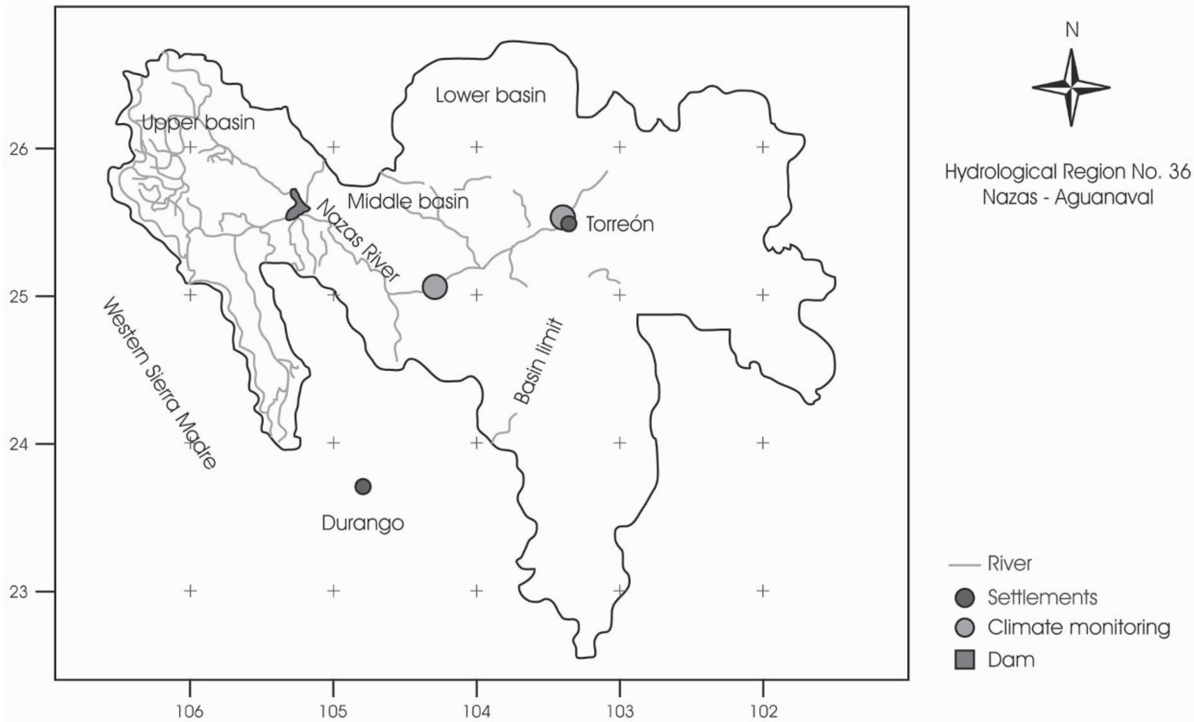
At the same site where the Davis station is located, there is an A-type evaporimeter tank (10 metres distant from the station), which was used to measure daily evaporation at 8:00 a.m. and taking into account also the days with precipitation, and to subsequently calculate the ET_0. Tank structure and dimensions, as well as site conditions, complied with FAO standard specifications (Allen et al., 1998).

13.4 Evapotranspiration Estimation Methods

The major inconvenience when measuring evapotranspiration at a regional scale and at a basin level is that any direct measurement technique is relatively expensive, hence the importance of proving the usefulness of semi-empirical models for a particular zone where climate variable data are available.

Climate information recorded at the stations located in the lower and middle basins was used to estimate ET_0 on a daily basis by the Penman-Monteith

Figure 13.2: Spatial distribution of automated weather stations in the Nazas Basin. **Source:** Authors' research data.



FAO, Hargreaves-Samani, and Doorenbos-Pruitt equations; then, a correlation was made with regard to Penman-Monteith FAO. Next, for the lower basin this study added ET_0 calculation on a daily basis from evaporation data and using the equation proposed by Cuenca (1989). Afterwards, a statistical comparison was performed between the ET_0 monthly average values obtained by the weather stations and the calculated values from the A-type tank. For this purpose, statistical indices were applied as correlation coefficient and systematic error or bias (*Bias* in equation 1), to measure the linear relationship between two quantitative variables and the model's tendency to underestimate or overestimate a variable,

$$Bias = \frac{1}{n}\sum\left(Q_{obs} - Q_{est}\right) \quad (1)$$

where Q_{obs} represents the observed value and Q_{est} the estimated value.

13.4.1 Penman-Monteith FAO Method

The Penman-Monteith FAO equation is the most precise available model. Variables used in this equation are solar radiation, air temperature, relative humidity and wind speed at 2 metres above the ground surface (Allen et al., 1998),

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_0 is the reference evapotranspiration [mm d^{-1}], R_n is the net radiation at crop surface [MJ m^{-2} d^{-1}], G is the soil heat flux density [`MJ m^{-2} d^{-1}], T is the mean air temperature [ºC], u_2 is the wind speed recorded at a 2-metre height [m s^{-1}], e_s is the saturated vapour pressure [kPa], e_a is the vapour pressure [kPa], e_s-e_a is the saturated vapour pressure deficit [kPa], is the slope of the vapour pressure curve [kPa ºC^{-1}], and γ is the psychrometric constant [kPa ºC^{-1}].

13.4.2 Doorenbos and Pruitt Method

The required climate variables are air temperature, relative humidity and wind speed during daylight hours, a and b coefficients of climate calibration as a function of relative humidity and wind speed during daylight hours, and a f_e factor as a function of the site elevation above sea level (Doorenbos/Pruitt, 1977),

$$ET_0 = f_e\{a + b[p(0.46 * T + 8.13)]\} \quad (3)$$

where ET_0 is the reference evapotranspiration [mm d^{-1}], f_e is an adjustment factor for the elevation above sea level, a and b are climate calibration coefficients, p is the annual daily mean insolation percentage, and T is the mean temperature [ºC].

13.4.3 Hargreaves and Samani Method

Inasmuch as its application demands air temperature and extraterrestrial solar radiation data (Hargreaves/Samani, 1985), this model represents a major option when attempting to process historical climate information, in which solar radiation is frequently unavailable from domestic weather station network data. However, for the same reason, namely that this model uses few variables, it is necessary to evaluate its usefulness at a regional and local level,

$$ET_0 = 0.0023(t_{med} + 17{,}78)R_0 * (t_{\max} - t_{\min})^{0.5} \quad (4)$$

where ET_0 is the reference evapotranspiration [mm d^{-1}], t_{max} is the daily maximum temperature [ºC], t_{min} is the daily minimum temperature [ºC], t_{med} is the daily mean temperature [ºC], and R_0 is the extraterrestrial solar radiation [mm d^{-1}].

13.4.4 A-Type Evaporimeter Tank Method

Daily evaporation data observed in the A-Type Evaporimeter Tank can be expressed in terms of ET_0 data by using the following formula:

$$ET_0 = K_p E_{pan} \quad (5)$$

where ET_0 is the reference evapotranspiration [mm d^{-1}], E_{pan} is the evaporation observed in the tank [mm d^{-1}], and K_p is the tank coefficient. Kp, derived from the equation proposed by Cuenca (1989), was employed to calculate ET_0 with this method, using average values of wind speed and relative humidity at the tank site.

This method has confirmed its practical value, and it has been successfully applied to calculate ET_0, since evaporation measurement incorporates the effect of radiation, wind, temperature, and humidity at a specific site. In some experimental works, evaporation values measured in the A-type tank, affected by their corresponding correction factors, have been used to calculate the irrigation water volume to be replaced in crops (Godoy/López, 1997; Tijerina, 2000; González/Hernández, 2000).

13.5 Results and Discussion

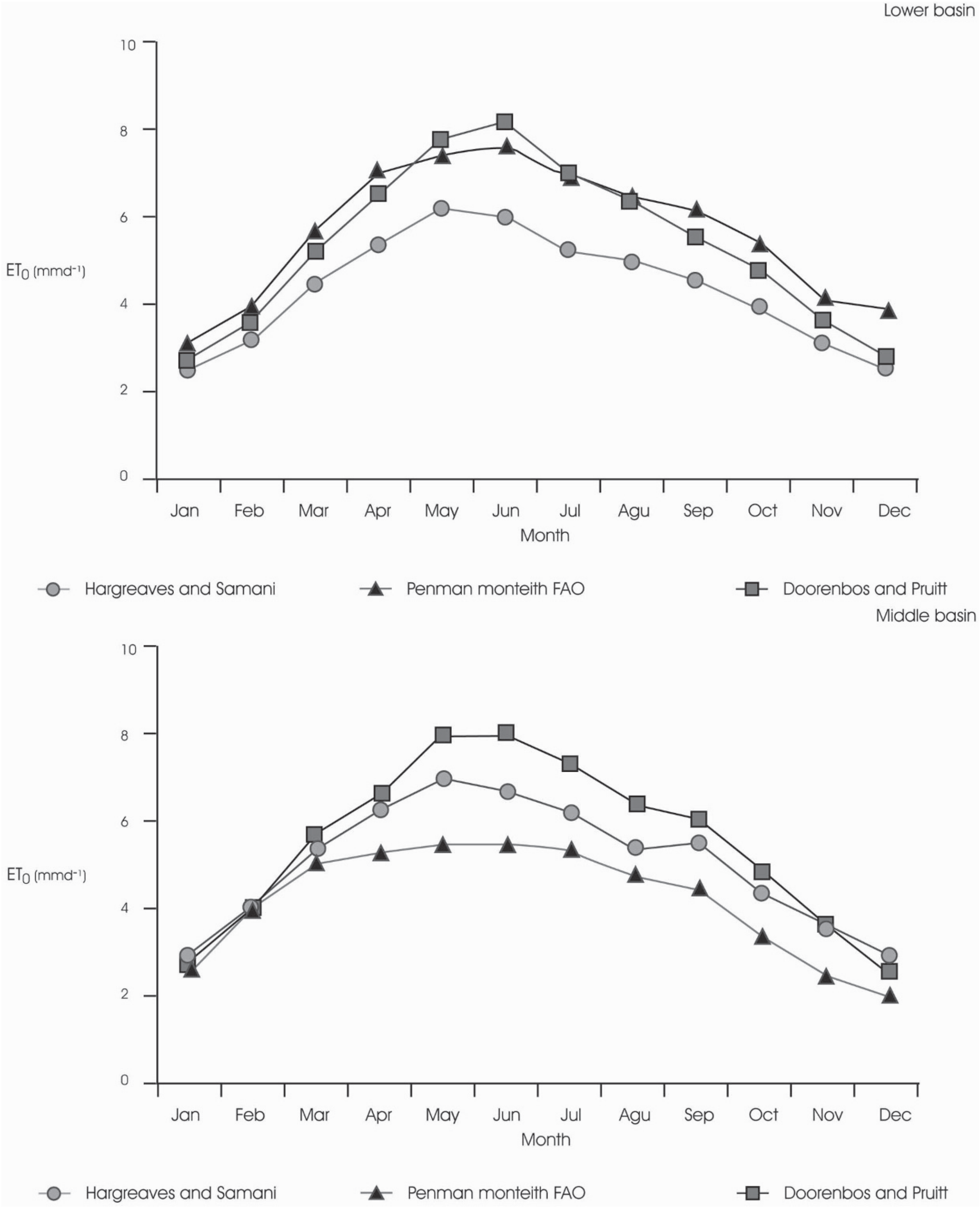
13.5.1 Reference Evapotranspiration

Climate information from three observation cycles (years 2005, 2006 and 2007) was used to estimate ET_0 in the lower and middle Nazas River basins; these data were recorded by the autonomous stations already described for each sub-region. Estimations in daily periods were then made, using the Penman-Monteith FAO, Doorenbos-Pruitt and Hargreaves-Samani models. However, for the purpose of data appreciation, these are shown in daily average values per month, after having averaged all three observed cycles. Subsequently, a simple correlation was performed between ET_0 obtained with the Doorenbos-Pruitt and the Hargreaves-Samani methods, and that obtained by the Penman-Monteith FAO model.

Figure 13.3 shows the results for our study sites. In this figure it is possible to observe an evident difference between the lower and middle basins using the Penman-Monteith FAO equation, and not a very noticeable one with the Doorenbos-Pruitt equation, with evapotranspiration in the lower basin being greater. But with the Hargreaves-Samani equation it is also possible to appreciate a difference, albeit in the opposite sense: i.e., with evapotranspiration in the middle basin being greater. The reason for this result may correspond with two interrelated situations: the scarce climate information used by the method and/or its strong reliance on (extraterrestrial) solar radiation based on the site's geographic location, which therefore does not involve the orographic environment effect.

The lower basin (Davis station) presents similar ET_0 tendency patterns to the Doorenbos-Pruitt and Penman-Monteith FAO methods, showing minimum values at the beginning of the cycle (January) and maximum values at its middle (June), at a rate of 3 and 8 mm d^{-1} respectively, with this last value decreasing to a value between 3 and 4 mm d^{-1} at the end of the cycle (December). By contrast, the values obtained with the Hargreaves-Samani method are 2.5 (at the beginning and the end of the cycle) and 6.2 4 mm d^{-1} (at its middle) as minimum and maximum values, correspondingly. There is a time gap (May) in the maximum evapotranspiration value, a period which is signalled as the one with the greatest extraterrestrial solar radiation incidence. However, all three models coincide in the critical period, with the highest evapotranspiration being the months of April to September. Also, during this period a considerable difference can be

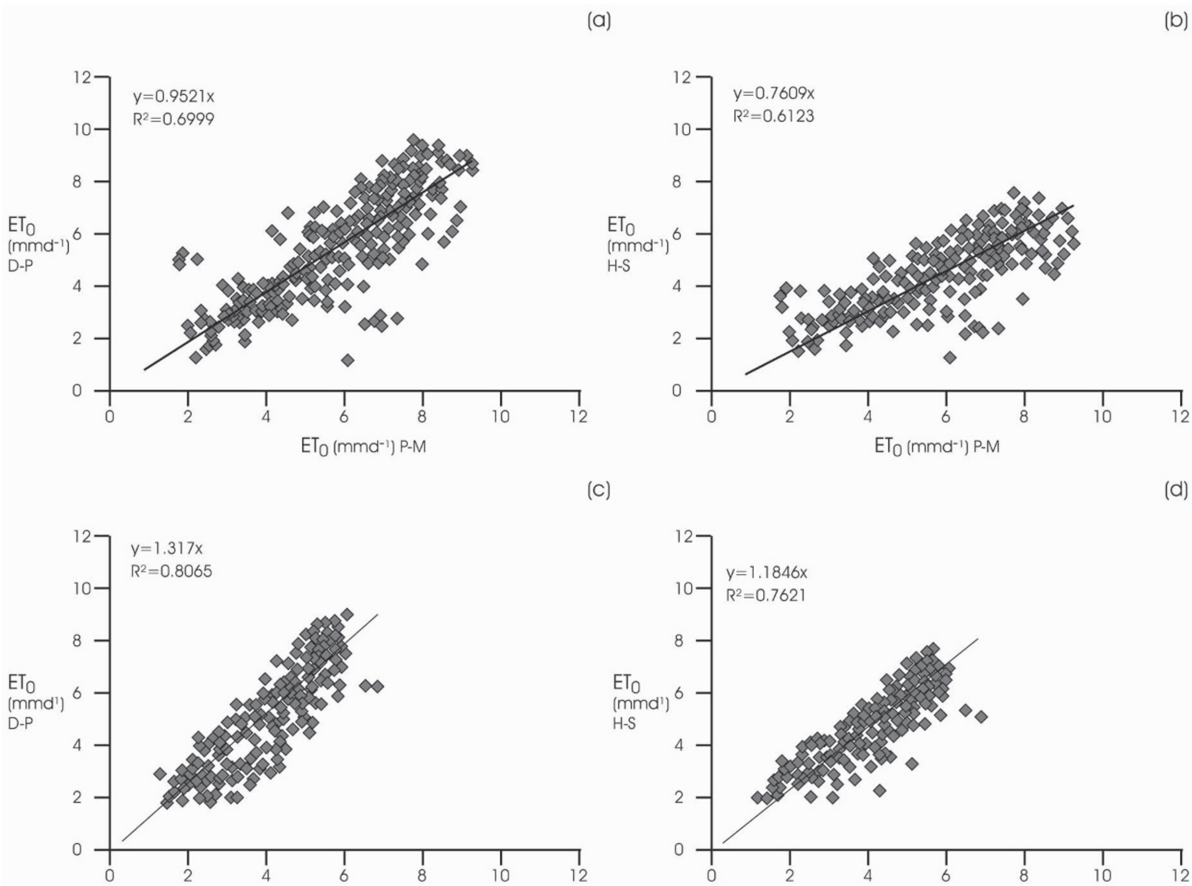
Figure 13.3: ET_0 behaviour, average of three observation cycles (years 2005, 2006 and 2007), in the lower and middle Nazas River Basins, using different methods. **Source:** Authors' research data.



observed in the results from all three models (up to 1.8 mm d^{-1}).

The middle basin (Adcon station) presents tendency patterns similar to those presented by the lower basin, with the critical period being April to Septem-

Figure 13.4: Estimate of ET_0 using the methods of Doorenbos-Pruitt 'D-P' and Hargreaves-Samani 'H-S', compared with ET_0 using the Penman-Monteith FAO method 'P-M', in (a) and (b), respectively, for the lower basin, and (c) and (d), using the same framework, for the middle basin for the 2005, 2006, and 2007 period average. **Source:** Authors' research data.



ber, with evapotranspiration discrepancy in the results from all three models for this same period, but with a greater contrast (up to 2.5 mm d^{-1}).

It is evident that the Penman-Monteith FAO model presented a greater, somewhat 'logical', sensitivity to change, due to the fact that climate variables such as temperature, wind speed, and solar radiation evidenced higher values in the lower basin as compared to those in the middle basin.

In addition, a correlation was performed between these models in order to note the usefulness of those with lower demand for climate variables, as compared to the one requiring most climate variables defining evapotranspiration. In this case the Doorenbos-Pruitt and Hargreaves-Samani models were compared with the Penman-Monteith FAO model. Figure 13.4 shows the results, indicating acceptable correlations, with the Pearson correlation coefficient being 0.69 and 0.61 for the lower basin, and 0.80 and 0.76 for the middle basin with the Doorenbos-Pruitt and Hargreaves-Samani models, as compared to the Penman-Monteith FAO method, respectively. The Pearson coefficients are slightly higher for the middle basin, due to the fact that there is a minimum difference during the first months of the period (January, February, and March).

13.5.2 Comparison of Methods

The comparison of the methods was performed solely for one observation cycle (2005) and during the critical or high evapotranspiration period, covering the months of May, June, July, and August. It has to be considered that all three models used evidence from the maximum water demand during this period, and it is also this period that presents a marked difference in the estimation of ET_0 with all three models. This comparison consisted in performing a correlation of ET_0 monthly average values, determined by the A-type evaporimeter tank (equation four) against

Table 13.1: Average monthly ET_0 values in the lower basin during the maximum water requirement period (May–August). **Source:** Authors' research data.

Method	ET_0 (mm d^{-1}) monthly average				Correlation Coefficient	Bias %
	May	June	July	August		
A-type tank	6.902	8.001	7.571	6.166	-	-
Penman-Monteith	7.817	8.297	7.790	6.345	0.913	+5.614
Doorenbos-Pruitt	8.372	9.821	7.912	6.794	0.861	+14.860
Hargreaves-Samani	6.339	6.696	5.447	5.109	0.646	-17.625

monthly average values obtained by the Penman-Monteith FAO, Doorenbos-Pruitt, and Hargreaves-Samani models.

The results are presented in table 13.1. This table shows that the Penman-Monteith FAO and the Doorenbos-Pruitt methods overestimate ET_0 by 5.61 and 14.86 per cent, with a *correlation coefficient* (cc) of 0.91 and 0.86, correspondingly. On the other hand, the Hargreaves-Samani method underestimates it by 17.62 per cent, with a cc of 0.74 during the period analysed. According to De Juan (1993) the correlation coefficients obtained may be considered as acceptable when referring to very high correlations. The obtained bias and cc are noteworthy evidence that the Penman-Monteith FAO model is highly precise for this region, followed by the Doorenbos-Pruitt model, and finally by the Hargreaves-Samani model.

13.6 Conclusions

Except for Hargreaves-Samani, the models used the evidence of a higher reference evapotranspiration in the lower Nazas River basin as compared with the middle basin, confirming that this corresponds to two completely different conditions, more clearly during the March–September period. For water management this means a greater demand for water by any crop established under the lower Nazas River basin climate conditions.

Among the methods analyzed regarding the evaporimeter tank, it may be presumed that the Penman-Monteith FAO method is highly precise in estimating reference evapotranspiration in the lower basin. However, when not enough variables are available, it is also suggested that the Doorenbos-Pruitt method should be used as a second option, and as a last alternative the Hargreaves-Samani model, although in this case it is suggested that studies at a local level be also performed in order to calibrate this model and improve its usefulness.

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Part III Water Quality, Pollution and Health

14 Potable Water Use from Aquifers Connected to Irrigation of Residual Water

Juana Enriqueta Cortés Muñoz and César Guillermo Calderón Mólgora

14.1 Introduction[1]

Four important challenges arise when seeking to use an aquifer for potable water that is recharged with wastewater through farmland infiltration: a) to precisely determine organic compound concentrations, primarily non-regulated and emerging; b) to identify pathogenic and opportunistic micro-organisms of different taxa; c) to establish an efficient and economic water treatment system for purification, and d) to estimate and prevent possible impacts on public health and the environment from purification residues.

This chapter provides a methodological approach to the problem of water quality and emerging contaminants in an aquifer, with the focus on sanitary risk; in other words, probability-prevention of adverse effects on public and environmental health. Initially, it was essential to establish groups of contaminants in accordance with their physico-chemical characteristics, size and molecular structure, for the purpose of providing compound indicators for the treatability tests in the laboratory and on-site. Once the contaminants that can serve as indicators of the presence of emerging contaminants in a contaminated aquifer have been established, the next step is to determine the most appropriate type of treatment for their removal and disposal, taking into account that the water is required for human consumption.

14.2 Background

Water is the main component of living organisms and is therefore a primary necessity for human and economic development in Mexico. Invariably, low quality of water is associated with a low standard of living and the presence of diseases caused by enteric pathogens or chemical contaminants, which affect the social and economic environment of the inhabitants who do not have access to it. Consequently, its availability must be viewed on the basis of quantity and quality (Elimelech, 2006), which are defined through a series of parameters that must be controlled by those responsible for providing water services to the population.

In addition to access to potable water being affected by problems that arise in the contamination control of supply sources from emissions and discharges associated with economic activities, domestic discharge represents one of the main sources of contamination, due to the indiscriminate use of detergents, whiteners, suntan lotions, softeners, fragrances, shampoos, and other personal care items, as well as pharmaceuticals, plasticizers, and fire propellants and retardants, which have recently emerged as contaminants that impact on public health, wildlife and the environment in general (Lopez/Barceló, 2008).

As a result of today's urban lifestyle, a large volume of wastewater and solid residues of variable composition is spilled into the environment, where a broad range of pathogenic micro-organisms and polluting chemicals can potentially affect public health and the environment. Of particular sanitary importance are the emerging and re-emerging pathogens, as well as non-regulated and emerging chemical contaminants that can also enter environmental compartments through different routes and mechanisms (figure 14.1).

The contamination of water resources can occur directly when spilling raw or treated wastewater discharge into receiving surface water bodies, or indirectly when disposing of wastewater, excreta, or solid waste into the ground, where, after adsorption, transformation, leaching, and infiltration processes (Papadopoulou et al., 2007), there is a possibility that the microbiological and chemical quality of the groundwater will be altered.

1 Keywords: Emerging contaminants, contaminated aquifers, potable water, potabilization, membrane processes.

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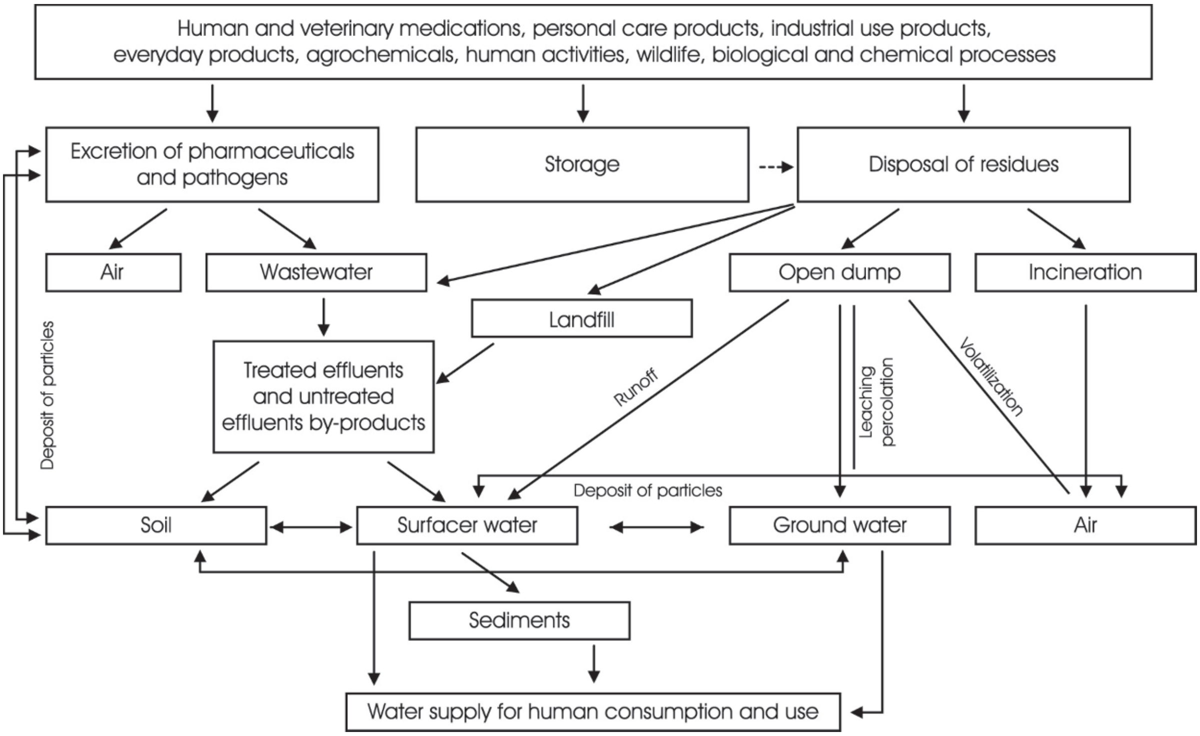
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_14,

Figure 14.1: Routes of entry of emerging contaminants into the environment and potable water. S**ource:** Adapted from Blasco and Dell Valls (2008).



Emerging contaminants are previously unknown or unrecognized contaminants that may have been present in the environment, but that have recently generated concern over their possible short- and longer-term impacts (Lopez/Barceló, 2008). These may include chemical substances of anthropogenic origin that are frequently incorporated into the atmosphere and that may be dangerous even if they are not persistent.

The following list includes a broad range of everyday waste products (table 14.1), some of which have recently been included in the list of high-priority substances in water, others that are candidates for regulation, and others that are considered a research priority (Jacangelo et al., 2006).

Despite the fact that analytical techniques have evolved sufficiently since the 1990s to detect some organic compounds in concentrations as low as parts per trillion and allowed the identification of a broad range of pharmaceuticals, personal care products, pesticides and veterinary products in surface water (Kolpin et al., 2002; Tixier et al., 2003) and groundwater (Sacher et al., 2001), relatively little is known about the presence of these types of contaminants and their transformations and impact on different environmental compartments or the risks to public health, water and land organisms and wildlife (Blasco/DelValls, 2008). This is why they have not yet been fully regulated and why the availability of methods for their analysis in the laboratory remains limited (Richardson, 2003; Gross et al., 2008).

Some conventional purification water treatment processes have shown a substantial yet incomplete degradation of, or the removal of, organic compounds (Stackelberg et al., 2007), so in reality the effectiveness and efficiency of the treatment processes for the removal, transformation or inactivity of this type of contaminants is unknown, as are the effects of disinfectants on emerging and re-emerging pathogens. Furthermore, the negative effects are not necessarily associated with a high persistence. In this case, high production and consumption of these contaminants is relevant, as is their continuous introduction into the environment.

Even though some pesticides are now subject to legislation in Mexico, they recently sparked renewed interest because degradation or transformation products are sometimes as toxic as, or more toxic than the original molecule (Escher et al., 2008). Awareness of the risk of agents such as perfluorinated detergents or pharmaceuticals in the environment is relatively recent and so there is still not enough information to carry

Table 14.1: Some emerging chemical pollutant groups. **Source:** Results from the research team,

Personal care products	Frequent use products	Human and veterinary pharmaceuticals	Miscellaneous
Fragrances Hair care Dental care Skin care Suntan and blocks Surfactants Bath additives	Flavourings Condiments Dyes Food preservatives Goods preservatives Surfactants Some stimulants Cleaning products	Hormones Antidepressants Analgesics and anti-inflammatories (non-steroidals) Antipyretics Antibiotics Anti-epileptics Lipid and glucose regulators Antitussives Antihistamines Bronchodilators Blood pressure regulators Anticoagulants Histamines Drugs of abuse Metabolites and breakdown products Others	PCBs Polyaromatic hydrocarbons Petroleum hydrocarbons Veterinary products Pesticides Domestic insecticides Deodorizers Synthetic dyes Fire retardants Organotins Plasticizers (phthalates) and anti-corrosives Solvents Non-essential metals and metalloids Perfluorinated compounds Disinfection by-products

out a proper valuation of their impact. Furthermore, many of them, including bromate fire retardants, alkylphenol ethoxylate detergents, and some pharmaceuticals, are endocrine disruptors with a potential to alter growth, development, reproduction and neurobehavioural performance in animal and human models. One of the better documented evidences is the feminization of superior water organisms (Fent et al., 2006).

As concerns pathogens, of the 1,407 species of micro-organisms that are known as disease producers in human beings, 177 (13 per cent) of these species are considered emerging or re-emerging and 77 (37 per cent) of these are viruses or prions; 54 (10 per cent) are bacteria; 22 (7 per cent) are fungi; 14 (25 per cent) are protozoa and 10 (3 per cent) are helminths. These pathogens are not associated with specific animal hosts and can persist in different animal reservoirs – mammalian or not – and possess a biological flexibility that allows them to take advantage of the epidemiological opportunities that arise (Woolhouse/Sonya, 2005).

The emerging, re-emerging and non-regulated hydro-transmissible pathogens (table 14.2), include organisms that use a faecal-oral route as the primary transmission route. These may include *Cryptosporidium*, *Escherichia coli* O157, rotavirus, hepatitis virus and norovirus (or Norwalk virus), and other bacteria like *Legionella* that use different routes of transmission. Thus, the importance of water in the transmission of organisms recognized as emerging pathogens is continuously being evaluated with the new technological epidemiologist tools available. *Helicobacter pylorus* is a pathogen example that emerged as a potentially hydro-transmissible bacterium (Shahamat et al., 1993).

There have been few projects in Mexico related to the presence of emerging contaminants in wastewater and natural and potable water and these have all been developed in the Mezquital Valley where Irrigation Districts 03 and 100 are located. These areas use raw sewage water from Mexico City to irrigate farm crops. This water then recharges the Tula aquifer that supplies potable water to the inhabitants of the area.

It is clear that knowledge about these contaminants and their sanitary and environmental impacts is a problem that must be approached holistically with a focus on risk, mainly because four important challenges arise when the intention is to use an aquifer recharged with farmland wastewater from natural infiltration for potable purposes. We must:

a.) precisely determine organic compound concentrations, primarily non-regulated and emerging;
b.) identify pathogenic and opportunistic micro-organisms of different taxa;
c.) establish an efficient and economic water treatment system for purification, and
d.) estimate and prevent possible impacts from purification residues on public health and the environment.

Table 14.2: Potentially hydro-transmissible emerging, re-emerging and non-regulated pathogens. **Source:** Results from the research team.

Bacteria	Viruses	Protozoa
Aeromonas hydrophila *Escherichia coli* (pathogen strains) Helicobacter pilori Mycobacterium avium *Salmonella* spp *Shigella* spp *Vibrio* spp *Yersinia* spp	Bacteriophage Adenovirus Calicivirus Coxsackievirus Echovirus Norovirus Rotavirus Poliovirus Hepatitus virus	Free life ameoba (*Acanthamoeba*) Entamoeba histolytica Cyclospora cayetanensis Giardia lamblia Naegleria fowlery Microsporidia Toxoplasma gondii

14.3 Objective

To provide a methodology to respond to the presence of emerging contaminants in raw and treated wastewater used in farm irrigation and its impact on the water quality of an aquifer used for potable water supply, with a focus on public and environmental health.

14.3.1 Application in an Area of Interest and Current Situation

The Valle del Mezquital, located in the state of Hidalgo (figure 14.2), is a clear example of an aquifer recharge with raw and partially treated wastewaters based on its reuse in farming irrigation of approximately 90,000 hectares in Irrigation Districts 03 Tula (dependent on the Requena dam) and 100 Alfajayucan (dependent on the Endhó dam).

The aquifer of Valle del Mezquital is a source of potable water that helps to support the needs of Mexico City. Various water quality studies of groundwater have been carried out to evaluate water treatment technologies for the purification of water. These include the determination of some emerging organic contaminants, as well as some pathogens.

The study carried out by Downs et al. (1999) in Tezontepec and the Colorado Cerro spring concluded that nitrates are a water quality problem, and detected eight semivolatile non-regulated contaminants, seven polychlorinated biphenyls, and 11 trace metals.

Later, the same authors (2000) integrated chemical and microbiological tracers into a 'general panorama' to compare the effectiveness of two natural treatment processes in accordance with the site, water type, sampling day and indicator: a) an irrigation channel and a stabilization-storage dam – comparing on-site surface water samples before and after storage, and b) ground infiltration – groundwater flow – comparing surface water samples with groundwater samples (groundwaters adjacent to and near the site). The study concluded that semivolatile organic compound removal is efficient using a process that combines volatilization, photolysis, biodegradation, sorbing, precipitation and sedimentation. The ground appears to operate like a slow sand filter. Most likely removal during the groundwater flow is the dominant process. The study suggests that the environmental conditions (high temperature, large amounts of substrate for the micro-organisms, high level of insulation and retention times in dams and channels) appear to encourage natural degradation processes. However, the study considers that since the system was not completely evaluated, important potential risks to public health may exist.

Jiménez et al. (2004), analysing the wastewater of the Mexico City and Tula aquifers, concluded that the supply sources show low concentrations of emerging contaminants; however, there are exact sources showing the presence of carbamazepine, nonylphenols and salicylic acid and they do not comply with the maximum permissible limit for total dissolved solids, aluminium nitrates and fluorides (Jiménez and Chávez, 2004). They also detected bacteria, bacteriophages and protozoa in some wells, springs, and watermills.

These studies generally conclude that the ground treatment capacity in Valle del Mezquital produces an aquifer of 'acceptable quality', yet they recommend advanced treatment for potable use, changes in the regulations and research into the transportation and removal of contaminants. There is still no evidence to be found in available information on the determination of persistent contaminants such as some sulfa or synthetic type antibiotics, polychlorinated biphenyl, or aromatic hydrocarbons and dyes, among others. Also, the contaminants that are generated inside Valle del Mezquital as a result of the different economic ac-

Figure 14.2: Localization of the Mezquital Valley. **Source:** Google Earth.

tivities (for example: dental clinics, agro-chemical clinics and hospitals, doctors' surgeries, residues generated by cattle, veterinary products, or hydrocarbons from the refinery at Tula) were not identified either.

It is also important to consider that in the case of emerging pathogens, veterinary antibiotic use to promote animal growth encourages resistance to drugs that were used initially or were eventually developed for use by humans. The emergence of this resistance to bacteria possibly occurs with exposure to concentrations lower than the detection limits of current methods used in the monitoring systems (Smith et al., 2002).

The situation inside the Tula Valley allows us to assume that the water issue is complex, particularly if we also consider that there are 128 deep wells, 61 springs and 18 diverse sources (watermills, galleries, conduction lines, rivers). It is important to take into account that the different uses of the ground: residential, agricultural, cattle and industrial, with their variants (petrochemical, textile, cement, limekiln, metallurgical, electrical energy, veterinary products, foods, manufacturing, chemical, and agrochemical), can affect public and environmental health.

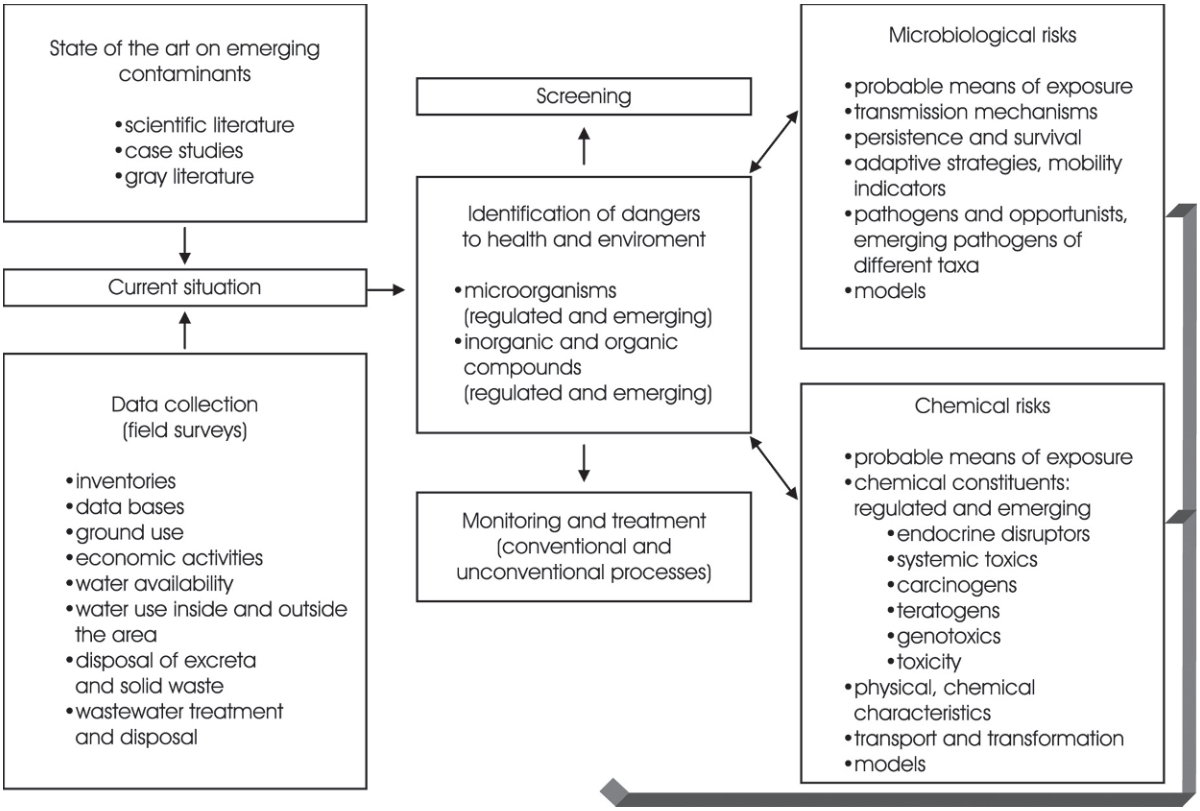
It is not known whether the wastewater treatment systems operate efficiently in the five municipalities that have them or what type of control exists for the disposal of solid waste that can alter the quality of groundwater through leaching.

14.4 Methodology

A study of this nature requires a holistic approach with a focus on sanitary risk (figure 14.3); in other words, a probability-prevention of adverse effects on public and environmental health with the application of methodologies to evaluate environmental and public health risks, as well as the identification of high-priority emerging contaminants for the recharge process of the aquifer, considering short- and long-term impacts. For example:

a.) micro-organisms (environmental reservoirs, pathogenicity, infective doses, latency, adaptive strategies, persistence and resistance to treatment and disinfection processes);
b.) chemical contaminants (neurotoxicity and other systematic poisonous effects, genotoxicity, estrogenicity, carcinogenicity, among others);
c.) identification and analysis of national, regional, and international regulations concerning natural

Figure 14.3: Sanitary risk focus to respond to the problem of aquifer recharge in an irrigation zone with raw sewage water. **Source:** Results from the research team.



and artificial recharge of aquifers for potable use (opportunities and barriers);

d.) determination of the capacity of existing purification systems for the removal of emerging contaminants.

14.5 Proposed Methodology

The methodology proposed as an alternative solution for this problem has various stages:

14.5.1 Screening

The relevant questions are: What contaminants are present? What concentrations are present in the water? How often are they spilled into the water? What are the possible mechanisms for transformation? In what other environmental compartments could they be present?

14.5.2 Information Review and Analysis

To respond to these questions it is essential to carry out a state-of-the-art study on the physicochemical and microbiological parameters of sanitary and environmental importance in plans to recharge aquifers for potable use, with the objective of establishing the universe of emerging and non-regulated contaminants.

In the case of the Valle del Mezquital aquifer, the recharge is basically through infiltration or percolation of raw sewage (coming from Mexico City) or partially treated sewage (the hydro-agriculture infrastructure eliminates some suspended pathogens, solids and some chemical contaminants) that is used for crops (Downs et al., 2000). Consequently, it will be necessary to review the diffusion processes and the ground-aquifer systems to determine the destination of the contaminants in the recharge site, including particulated matter, dissolved organic components, nutrients (nitrogen, phosphorus) and micro-organisms, always keeping in mind public and environmental health protection.

It will also be necessary to identify precise and non-precise sources of contamination within the Valle del Mezquital, since these impacts on surface water quality, the ground and potentially the leachates that infiltrate the aquifer.

14.5.3 Pre-screening of Contaminants

The identification of danger includes a screening of the possible contaminants that arrive at the aquifer from wastewaters used in irrigation, as well as those produced in the recharge zone as a result of farming practices and other industrial activities in the zone. This can be carried out through surveys that allow data to be obtained on the use of agrochemicals (inventories), wastewater discharge (industrial inventory), availability and uses of groundwater, disposition of excreta and solid waste, and treatment and disposal of wastewaters.

An important challenge is posed by the products used in personal care, different daily activities, products used in industry, pharmaceuticals for human and veterinary consumption (including hormones), and the consumption of illegal drugs. The most important compound groups considered in the specialized international literature are:

- brominated fire retardants;
- disinfection sub-products;
- gasoline additives;
- hormones and other endocrine disruptors;
- organometallic (organotin) compounds;
- perfluorinated compounds;
- pharmaceuticals and personal care products;
- polar pesticides, their degradation and metabolite products;
- surfactants and their metabolites; and
- organophosphate fire retardants and plasticizers.

It is possible to obtain data by consulting the databases of environmental agencies in different countries, specialized databases, case studies, environmental monitoring programme reports, listings of high-priority substances, and basic medicine charts of the Ministry of Health (SSPA), as well as information available in other national institutions. For example, the following are some of the most common pharmaceutical products in Mexico:

- antibiotics: sulfa drugs, penicillin, tetracycline;
- stimulants: caffeine and other prescribed stimulants;
- antiasthmatics and bronchodilators: cimetidine, salbutamol;
- stimulant medications and anti-depressants;
- analgesics and anti-inflammatories: antipirine, codeine, hydrocodone;
- hyperglycaemics: metformin;
- antipyretics: acetaminophen;
- blood pressure control: dialtiazen, nifedipine;
- histamines: ranitidina;
- hormonal therapy: antioestrogenics, ovulation promoters, birth control.

The information is concentrated into a matrix, where lists can be cross-referenced. The frequency with which the agents are spilled into the environment will become a basic selection criterion to monitor a particular polluting agent in the study. Physicochemical and persistence chemicals will also be considered, as will biomagnification and bioaccumulation capacities.

14.5.4 Prioritization of Contaminants

Prioritization is based on the application of risk assessment methodology for public and environmental health. Particular care must be taken with agents from the list of contaminants obtained in the previous phase that appear in the scientific literature with enough evidence to conclude that they have a toxicological effect and that they are frequently detected in industrial and municipal waste products. Viruses and other pathogens in non-cultivable viable state must also be considered, along with nanomaterials.

Also, the observable effects in environmental exposures (figure 14.4) that appear over the long term or where concentrations in the water are generally small must also be kept in mind. When speaking of dangerous and emerging chemical contaminants, the concentrations are arranged in order of pico-, nano-, and micrograms per litre.

The basic effects to include in a new matrix when considering what is appropriate for potentially exposed organisms are: birth and development defects, development retardation, neurotoxicity, cancer, effects on the endocrine system, gastrointestinal (including hepatotoxicity), hematological, hormonal activity, immune system (including sensitization and allergies), renal system, reproduction and fertility, skin, respiratory system, toxicity of wildlife and environment, persistence, bioaccumulation and biomagnification in water and on land, including humans.

The weight of evidence is an important criterion and for this assessment a scale of values and ranking aspects must be designed for the polluting agent, water organisms, wild flora and fauna, and more vulnerable sub-groups of the population such as developing organisms (tables 14.3 and 14.4).

Figure 14.4: Theoretical framework of the attempts to trace organic compounds and their relative significance for human health risks (prioritization). **Source:** Adapted from Asano and Cotruvo (2004).

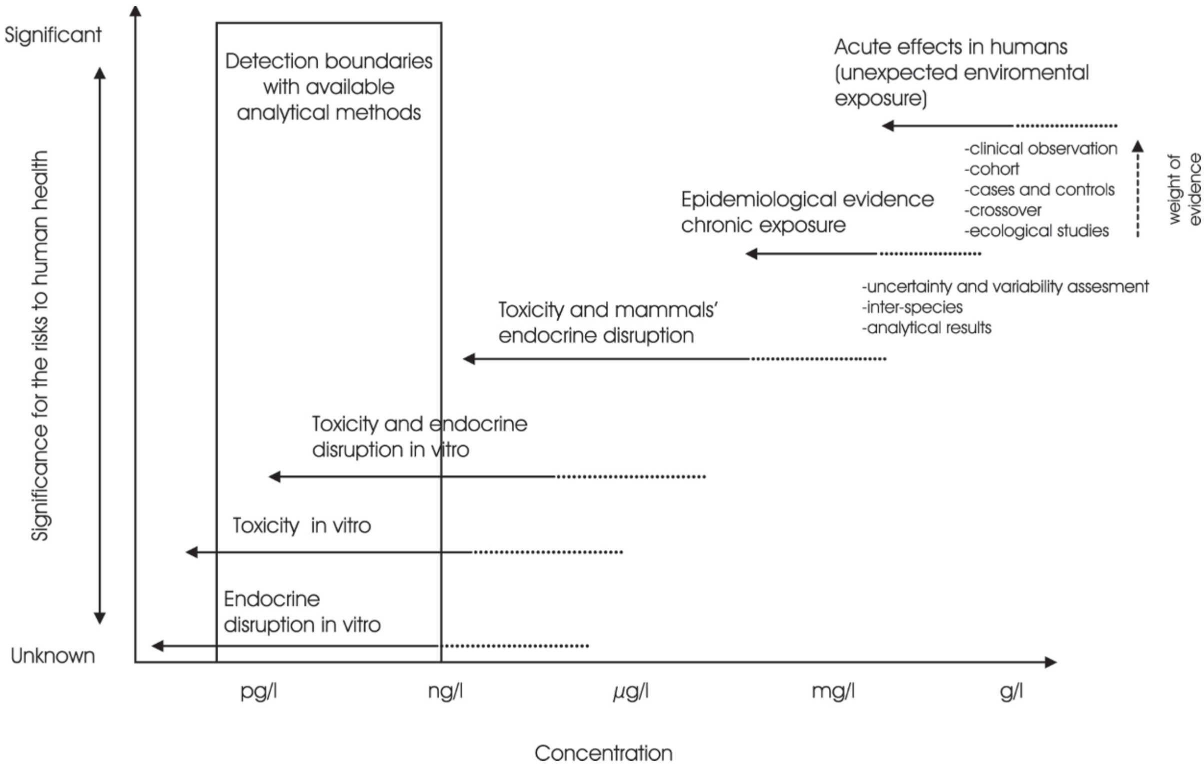


Table 14.3: Prioritization: effects of low dose chemicals. **Source:** Results from research team.

Effect on health	Most vulnerable group	Example of associated chemicals
Cancer	All	PAHs, some plaguicides, metals and solvents, PCBs
Cardiovascular disease	Particularly older adults	Arsenic, lead, cadmium, cobalt, calcium, magnesium
Reproductive: Quality and quantity of sperm, testicular function, fecundity and fertility, abortions, gender proportions, abnormalities in reproductive organs	Adults in reproductive years	PCBs, some pesticides organochlorides, some phthalates Endochrine disruptors
Development	Foetus and children	Lead, mercury, hormonal disruptors
Immune system	Foetus and children	Some endocrine disruptors
Nervous system disorders	Foetus and children	PCBs, heavy metals (mercury, lead, manganese, aluminium), organic solvents, some pesticides, some hormonal disruptors

It is important to mention that human experimentation has ethical limitations in cases concerning exposure to contaminants with unknown effects, so that it is often necessary to resort to the epidemiological evidence of observational studies as well as animal studies and test-tube models where it is not always possible to confirm causality.

14.5.5 Sampling and Sampling Analysis

Environmental assessment studies must also be included in prioritization studies. For example: destination and transformations in the environment, environmental monitoring, and ecological effects. In the Valle del Mezquital, the treatment 'capacity' of the hydro-

Table 14.4: High priority: hormonal disruptors. **Source:** Results from the research team.

Persistent organic contaminants	Polychlorinated biphenyls Dioxins DDT and metabolites	Alteration of the metabolism/transportation of steroid hormones (EH), interaction with thyroid hormone, neuroendocrine effects
Products used in farming and livestock	Insecticides Organochlorides Triazoles, imidazoles Triazines Diethyldithiocarbamate	Oestrogenic and/or androgenic effects EH biosynthesis inhibition Hypothalamus-hypophysis-gonadal Thyrostatic effects
Frequent use industrial products	Nonyl and octyl phenols Bisphenol A Some phthalates Polybrominated fire retardants Organotins Parabens UV-screen	Estrogenic agonist and receptors Estrogenic agonist receptor Prognana agonist, effects on the biosynthesis of the steroid hormone Interaction with prognana, altering homeostasis of the steroid and thyroid hormones Aromatase inhibitors Oestrogenic agonist and receptors Oestrogenic agonist receptor

Table 14.5: Wastewater and methods of analysis. **Source:** Results from the research team.

Bacteria	Virus	Protozoa
Aeromonas hydrophila *Escherichia coli* O:157 Helicobacter pylori Mycobacterium avium *Salmonella* spp *Shigella* spp *Vibrio* spp *Yersinia* spp	Bacteriophage. F+ Infect masculine stocks of E. coli (they have pili); specifically of faeces. Groups II and III are specifically of human stocks and I and IV of animal stocks Enterovirus	Free life amoebas *(Acanthamoeba)* *Entamoeba histolytica* *Cyclospora cayetanensis* *Microsporidia* *Cryptosporidium* *Toxoplasma gondii*
	Analytical methods	
Enrichment, isolation through selective means, identification through batteries of biochemical tests and serologic confirmation (ELISA)	Polymerase chain reaction (PCR) Bacteriophage plate count	Microscopy, including indicator culture and vital dye ELISA

agriculture infrastructure must be assessed; in other words, the storage effects on the water of the dams and the route of the water through the irrigation channels (table 14.5). To do this, samples of wastewater discharges that reach the areas of interest must be obtained, covering at least three sites considered influence sites for the aquifer in accordance with the following plan:

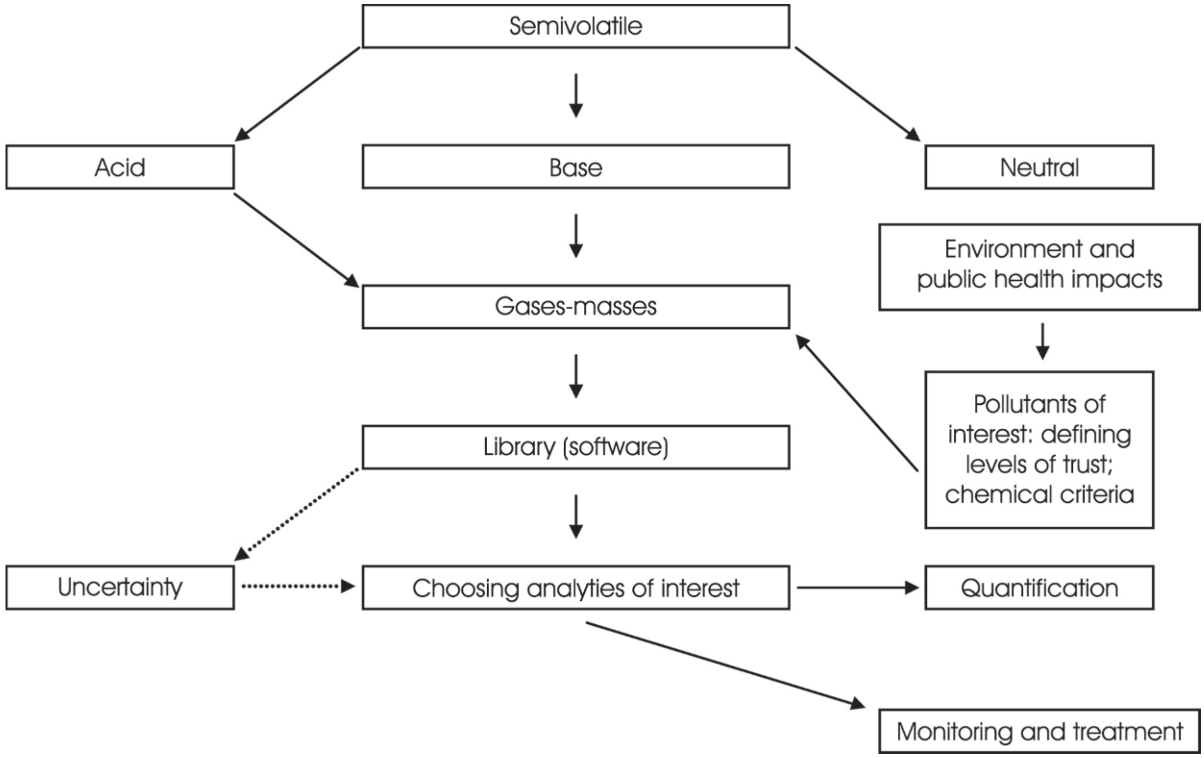
a.) *Bacteriological indicators*. Precise sample at time of greatest flow in accordance with national norms.
b.) *Pathogenic and opportunistic bacteria*. Concentration using Moore 24-hour hyssop, transported and preserved in mineral support until analysis in the laboratory.
c.) *Parasites and viruses*. Concentration in situ by means of filtration, in sample cartridges and specific pore size for each interest group.
d.) Establishment of analytical methods that allow the identification and quantification of microbiological contaminants in the laboratory, which may include any of the following:
e.) *Regulated, non-regulated and emerging organic compounds*. 24-hour composed sample, obtained, transported and preserved until analysis in accordance with national regulations and, if required, with the recommendations of international organizations or scientific publications.

Some studies suggest the use of formaldehyde to 1 per cent to prevent the degradation of some white compounds until the analysis. They also suggest that before the enrichment of the samples, they be filtered

Table 14.6: Methods for analyzing organic compounds. **Source:** Results from the research team.

Parameter	Method
Semivolatile and persistent organic compounds	Acid, base and neutral extraction. Gas chromatography/mass spectrometry
Pharmaceutical compounds	Chromatography of high resolution liquids/ Ionization/mass spectrometry
Antibiotics	Extractions for different groups. Extraction in solid phase, gas chromatography/ mass spectrometry
Hormones	Extraction in solid phase, gas chromatography/mass spectrometry

Figure 14.5: Strategy for the screening of semi-volatile organic compounds. **Source:** Results from the research team.



through fibre glass or cellulose, with a pore size that will depend on the content of organic matter.

Gas chromatography and high-resolution liquid chromatography are techniques par excellence in environmental analysis. They focus more on the analysis of non-polar and volatile compounds, non-volatile compounds such as pharmaceuticals and surfactants, personal care products, oestrogens and others, which can be determined after a derivation step.

It is advisable to obtain a second list of compounds for the different analysis methods from chromatograms and the available library, which should be compared with the theoretical list as well as with environmental and public health risk information systems (table 14.6). This will provide a definitive list of white contaminants or analytes of interest, which must be monitored twice more, to provide quantitative information of low water and rain. An example of the work strategy appears in figure 14.5.

14.6 Samples and Sampling Analysis

First, the relevance and efficiency of the methods of applicable treatment and disinfection must be analysed and then the treatability tests at the laboratory and directly at the site of interest must be carried out.

For the treatability test at the laboratory and on site, it is advisable to establish groups of contaminants in accordance with their physicochemical characteristics, size, and molecular structure, in order to have compound indicators. A first stage may consist of preparing a synthetic solution containing high-priority emerging contaminants, under controlled salinity conditions. In a second stage, it is possible to work directly with wastewater treated and enriched with the contaminants of interest.

Concerning purification, the use of nanofiltration membranes is a viable option for removing emerging organic contaminants because these types of systems consume less energy than inverse osmosis and produce water that requires minor amounts of remineralization. In some studies, nanofiltration membranes of a molecular cut of 200 daltons found on the market were tested and showed retentions of pharmaceuticals and hormones of up to 93 per cent with molecular weights between 194.2 and 318.1 g/mol, in addition to certain minerals (especially polyvalent cations and anions). Based on the quality of the rejections, it is important to analyse treatment alternatives such as oxidation-adsorption or advanced oxidation.

It is also advisable to carry out tests at the laboratory with contaminants of interest, and depending on the results, to test the most efficient method on a pilot scale (1 l/s), directly on the water supply source.

Another important aspect that must be taken into account in any kind of purification system that is found to be appropriate is the treatment and disposal of purification residues. The cost of this stage must be considered in the total cost of the treated water and must comply with regulations and available guidelines and recommendations.

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15 Evaluation of the Pollution of Hydrological River Basins: Priorities and Needs

Anne M. Hansen and Carlos Corzo Juárez

15.1 Introduction[1]

The pollution of the environment, particularly that of water and its relation to the population's health, is one of the most important water-related problems to be solved both in Mexico and globally (UN-WWAP, 2003). Assessment of pollution is therefore an obligatory step in solving any problem related to health and environmental risks.

International organizations have developed threshold values for contaminants in environmental compartments by observing the effects of particular compounds or chemical species in biological tests (Aidarov et al., 2002). These values are not comprehensive since they may vary seasonally, geographically, due to climate differences, and as a result of the hydrochemical, hydrobiological, and hydrological characteristics of the water bodies.

Traditionally, evaluation of water pollution is done locally (Troldborg et al., 2008) – for a particular place or site – without quantifying the contamination in the entire watershed. In contrast, if we take the hydrological river basin as the scale of the assessment, it becomes possible to improve the conditions of the rivers and to control the main sources of each type of contaminant (Meays et al., 2006).

The hydrological river basin is the geographic area where the hydrological cycle takes place. This area is delimited by the drainage divide, a topographical division inside which precipitation falls and drains into a stream or river. The *United States Geological Survey* (USGS, 2008) defines the hydrological cycle as the movement of the Earth's water. More specifically, it is the natural and repeated circulation of water in all its phases (liquid, gaseous, and solid) between the atmosphere and the Earth. Several phenomena occur between the hydrological cycle and the river basin, which determine the relation between the two and are conditioned by the geomorphologic characteristics of the river basin (Aparicio, 2001). Since the hydrological river basin is delimited by specific natural geographic conditions, which in turn determine the fate of contaminants discharged into it, it is also the basic unit for the analysis and formulation of solutions to water pollution problems.

Mexican water policy has established the hydrological river basin as the basic unit for water management, and it has allocated water for human consumption as a priority over other functions and uses of water (CONAGUA, 2008a). Water for human consumption must fulfil the quality standards indicated by official norms and ecological criteria (SEMARNAT, 2004). These guidelines include chemical contaminants categorized as *Toxic, Persistent, and Bioaccumulable Substances* (TPBS).

The *North American Commission for Environmental Cooperation* (NACEC) (a subsidiary of the *North American Free Trade Agreement* [NAFTA]) has adapted the following criteria to classify TPBS (NACEC, 2005):

- *toxicity*: adverse effect on human or environmental health;
- *persistence*: half-lives exceeding six months for soil and water and exceeding more than one year for sediments;
- *bioaccumulation* or *bioconcentration* factors larger than 5,000.

Previously, some TPBS were used to fight vector-borne infectious diseases and other plagues without knowledge of the secondary and environmental effects they may have caused. Currently, the effects of TPBS on human and environmental health are becoming better known (Fernández-Bremauntz et al., 2004).

World-wide actions to control the use and emissions of TPBS have focused on the most widely used and most dangerous substances, known as the *Persist-*

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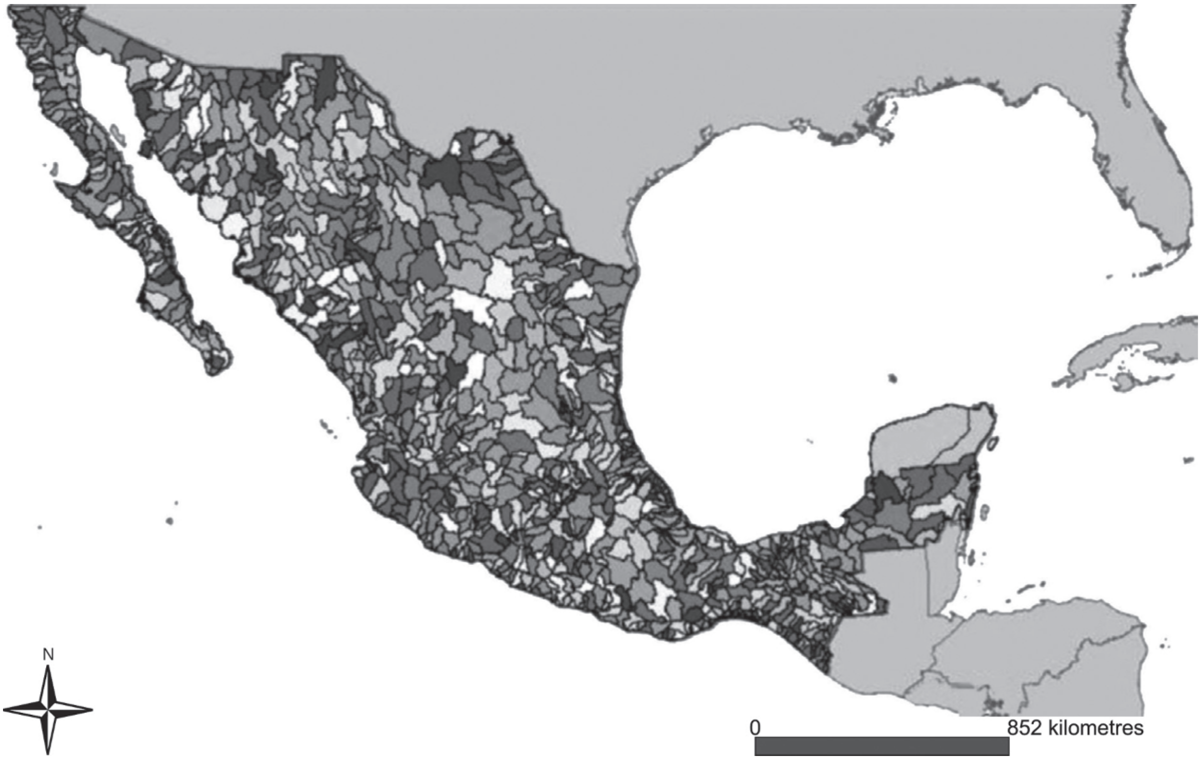
Figure 15.1: Delimitation of the Mexican hydrological basins. **Source:** CONAGUA (2009).



ent Organic Pollutants (POPs). With its incorporation into the Stockholm Convention, Mexico adopted a series of commitments that include research, development, and monitoring of TPBS in general and POPs in particular (Fernández-Bremauntz et al., 2004). Nevertheless, the long-term monitoring of TPBS has not yet been carried out in hydrological basins.

15.2 Objective

The objective of this chapter is to demonstrate the importance of the hydrological river basin as a reference unit for the decision-making process and for the solution of problems of TPBS pollution, and to define and exemplify actions to be included in such an assessment.

15.3 Water Management in Mexico

In Mexico, the hydrological river basin constitutes the basic unit of integrated water management. The 1,471 hydrological river basins (figure 15.1) are located in 13 hydrological-administrative regions (CONAGUA, 2008b). According to the National Law of Water (SEMARNAT, 2004; SARH, 1994), the *National Water Commission* (CONAGUA) is the highest authority over environmental water issues in Mexico. This commission is also the federal authority in charge of the prevention and control of water pollution.

Mexican water policy has adopted these priorities (CONAGUA, 2008a):

- to have sufficient water of suitable quality;
- to recognize the strategic value of water;
- to use water efficiently;
- to protect water bodies; and
- to guarantee sustainable development and environmental conservation.

In synthesis, the priority is to provide water of good quality to the population without causing risks to the ecosystems.

15.4 Methodology

To evaluate and solve pollution problems in hydrological river basins, the following actions should be included:

- creating inventories of pollutant sources;
- sampling and analysing environmental samples;
- evaluating the contamination; and
- modelling.

15.5 Creating Inventories of Pollutant Sources

An inventory of pollutant emissions in hydrological river basins consists of determining the amounts of polluting agents that are released from all types of sources in a given time period. Generally speaking, a water-polluting agent can be defined as any substance released into the hydrosphere which alters its natural composition and which produces adverse effects on humans, animals, vegetation or materials. Water pollution may be the result of a complex mixture of emissions from numerous sources, including industries, urban and domestic sources, soils, and run-off from livestock and agricultural activities.

The purpose of emissions inventories may vary according to specific needs and circumstances. For example, the objective for a single discharge is significantly different from an inventory of emissions for a whole hydrological river basin. The inventory of one discharge can be used to determine if it fulfils specific regulations, whereas the inventory of discharges in a hydrological river basin may sustain water quality programmes and may evaluate the possible environmental impact of multiple contaminant emissions.

Despite the differences between the two approaches, all types of inventories share the following objectives:

- identifying the categories of contaminant sources as well as the location and contribution of each;
- estimating the impacts on water quality through field studies and use of models;
- detecting temporal changes in emission levels;
- increasing efficiencies of methods, programmes, and procedures for water quality control;
- determining the technical specifications for control of wastewater discharges;
- adapting future planning, management, detection, and authorization to protect water from pollution; and
- reviewing the fulfilment of the established limits and guidelines.

To carry out discharge inventories in hydrological river basins, all emission sources should be integrated, including both point and diffuse sources. The methods used to collect and analyse data for these types of sources of pollutants are different. The point sources are those facilities, manufacturers, or activities that discharge in a specific location. Within this category are the majority of the industries, domestic discharges, and collected municipal discharges with and without treatment.

The diffuse sources of contaminants are more dispersed in the hydrological river basin, and they are studied collectively since the measured contaminants do not necessarily correspond to a single source. To ensure that the contaminant inventory is complete and to make the right decisions to solve pollution problems, it is important to identify and include diffuse contaminant sources. This category includes soil erosion, cattle farming, agricultural drainage, sediments as secondary sources of pollution, and contaminants originating from atmospheric transport and deposition. The latter may originate from sources located long distances from the hydrological river basin.

15.5.1 Sampling and Analysing Environmental Samples

Contaminant-monitoring programmes can be classified in two categories. The first type is for control of specific sources or contaminants and is intended for the monitoring of discharges. The second type is for control of the receiving water bodies and of the aquatic life that is exposed to contamination (Hansen et al., 2006).

In Mexico, long-term TPBS monitoring programmes do not exist. Consequently, there are no formal inventories or evaluations of exposures and of consequent risks. Existing monitoring programmes of non-TPBS substances include the *National Monitoring Network* (RNM) carried out since 1973 by CONAGUA, a programme which monitors the quality of surface and groundwater in the Mexican hydrological river basins. Its main objective is to characterize water physically, chemically, and bacteriologically, in order to define regulations and treatment systems for wastewater discharges and for water supplies. In 2007 the RNM included 1,014 monitoring sites (table 15.1). The Primary Network is a permanent component of the RNM aimed at generating long-term information that describes long-term changes in Mexico's most important water bodies. The secondary network is a component more flexible in time and space which monitors the shorter-term impacts of specific pollution sources in aquatic environments. This network supports regulations and pollution control. Results from special studies or case studies carried out by CONAGUA may also be included in the RNM.

Automatic networks of atmospheric monitoring are established in the main urban areas of the country, which provide information about standard atmos-

Figure 15.2: North America and MDN Sites. Blue symbols: active sites; white symbols: inactive sites. **Source:** NADP (2009).

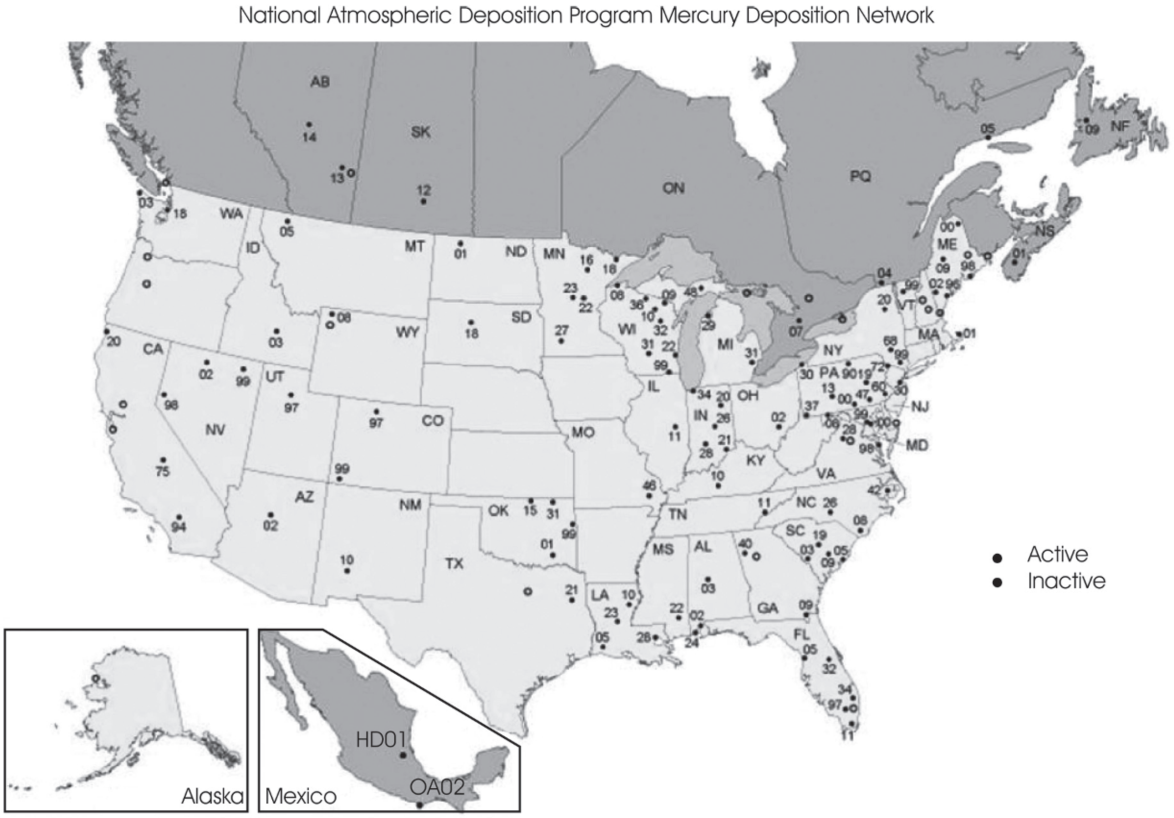


Table 15.1: Distribution of RNM Monitoring Sites. **Source:** CONAGUA (2008b).

<table>
<tr><th>Water Body</th><th>Primary Network</th><th>Secondary Network</th><th>Special Studies</th><th>Groundwater Reference Network</th></tr>
<tr><td>Surface water</td><td>207</td><td>241</td><td>81</td><td rowspan="2">89</td></tr>
<tr><td>Groundwater</td><td>130</td><td>25</td><td>123</td></tr>
<tr><td>Coastal water</td><td>52</td><td>19</td><td>47</td><td></td></tr>
<tr><td>Total</td><td>389</td><td>285</td><td>251</td><td>89</td></tr>
</table>

pheric contaminants (CO, SO_2, NO_x, O_3, PM_{10}, Pb, and HC).

None of these monitoring programmes incorporates routine measurements of TPBS. However, universities, research institutes, and centres for technological development carry out TPBS sampling and evaluation projects in environmental media and human tissue, financed by different Mexican government organizations like Mexican Petroleum (PEMEX), CONAGUA, state governments, and the *National Science and Technology Foundation (*CONACYT), as well as by private companies, international agencies like NACEC, and the World Bank. Nevertheless, these studies have specific objectives which often do not coincide and hence they fail to work towards the common goal of evaluating long-term trends in pollution. As a result, it has been impossible to determine changes in the state of the environment and to generate the information necessary for the creation of environmental policies to reduce or eliminate the risks related to TPBS exposure.

An exception to this is the *Mercury Deposition Network* (MDN), which operated two sites in Mexico from 2003 to 2006. MDN is coordinated through the USA's *National Atmospheric Deposition Program* (NADP), and it studies and quantifies the atmospheric fate of mercury and its deposition. MDN collects weekly samples for analysis of the deposition of mercury and methyl mercury in humid precipitation (rain and snow). Recent evidence suggests that the humid deposition of mercury from the atmosphere constitutes the main entrance of this metal into several ecosystems, rural as well as remote, that do not receive direct urban or industrial drainage (NADP, 2009). In 2003, through collaboration between the *Mexican Institute of Water Technology* (IMTA) and NACEC, MDN extended the monitoring area to include two sites in Mexico: HD01 in Huejutla, Hidalgo and OA02 in Puerto Angel, Oaxaca (figure 15.2). Both sites operated until 2006 (NADP, 2009).

Thousands of chemical substances, including TPBS, are produced and used annually worldwide (NACEC, 2005). Analytical methods for evaluating most of these do not exist. Also, due to budgetary limitations in the monitoring programmes, it has been necessary to focus only on those substances which are of major concern. Hansen et al. (2006) developed a methodology for NACEC to define high-priority TPBS to be included in a national programme of monitoring and assessment. This methodology consists of selecting certain TPBS which allow for an instant implementation of such a programme without the immediate need to change existing regulations and infrastructure.

These authors (Hansen et al., 2006) compiled information available on the internet on studies and monitoring of TPBS in Mexico and identified 1,056 studies carried out by 80 different Mexican institutions, mainly on metals and pesticides and, to a smaller extent, on *polyaromatic hydrocarbons* (PAHs), *polychlorinated biphenyls* (PCB), and *dioxins and furans* (D&F). Table 15.2 presents the study media, the types of PBTS, and the main institutions.

Official norms and criteria were analysed for different environmental media as well as the existence of infrastructure for chemical analyses of TPBS and the responsibilities for their monitoring and control (Hansen et al., 2006). Table 15.3 presents the proposed list of 17 individual TPBS or groups of TPBS for immediate implementation. It can be observed that 8 of the 12 Stockholm Convention POPs (Fernández-Bremauntz et al., 2004) are incorporated in this list. It is important to indicate that the proposed TPBS in table 15.3 should be considered an 'open list' that can be extended or reduced according to the needs and requirements of environmental investigations and human health risks. It is also worthwhile mentioning that these recommendations have been formulated for the implementation of an environmental monitoring and assessment programme and not for research or operational programmes aimed at controlling discharges.

To establish priority environmental media for monitoring TPBS, Hansen et al. (2006) identified those of main concern according to environmental policies and international commitments. They distinguished between monitoring aimed at protecting human health and at environmental protection.

Table 15.2: Compilation of Studies of TPBS in Mexico. **Source:** Hansen et al. (2006).

Medium	Number of Case Studies	Main TPBS	Main Institutions
Air	81	Metals, PAH	UNAM CENICA-INE INSP UAM CINVESTAV IMTA
Surface water	141	Metals, pesticides	IMTA UNAM UAS CIAD UABC
Groundwater and water for human consumption	33	Pesticides, metals	IMTA UNAM UANL IPN UAA
Sediments	93	Metals, pesticides	IMTA UNAM UAM IPN UABC
Soils and other solids	138	Metals, pesticides, PAHs	UNAM IMTA CP UANL INE
Biota	257	Metals, pesticides, PAHs, PCBs	UNAM CINVESTAV IPN CIAD UAS
Food	58	Metals, pesticides, dioxins & furans	UNAM
Human biomonitoring	255	Metals, pesticides	UNAM INSP CINVESTAV UAY UASLP
Total	**1056**		

The identified priority environmental matrix and their ranking for both monitoring objectives are presented in table 15.4. According to these rankings, monitoring of TPBS for the protection of human

Table 15.3: Proposed Starting List for Monitoring and Assessment of TPBS in Mexico. **Source:** Hansen et al. (2006).

TPBS	Air	Continental Water	Marine water	Water for human consumption	Sedi-ment	Soil and other solids	Biota	Food	Human biomoni-toring
Aldrin*				X				X	
Cadmium		X		X	X			X	X
Clordane*				X					
Chlorpyrifos								X	
Dieldrin*				X				X	
DDT*				X				X	
Endosulfan		X						X	
Endrin*								X	
Hexachlorocyclohe-xane (alpha, beta)								X	
Heptachloro*/ Heptachloro epoxide				X				X	
Hexachlorobenzene*				X					
Lead		X		X	X			X	X
Lindane		X		X				X	
Mercury		X		X	X		X	X	X
Metoxychlor				X				X	
Pentachlorophenol		X							
PCBs*							X	X	

*Included in the list of 12 POPs

health should focus on the monitoring of food and water for human consumption as pathways for exposure. Both matrices are included in the Mexican regulations and the monitoring of these media could be optimized with little difficulty to include TPBS. Human biomonitoring provides information on the accumulation of TPBS and may help define populations more exposed to these substances. Nevertheless, few reference studies exist, making it difficult to elucidate the outcomes. This same problem appears when atmospheric TPBS results are interpreted. The protection of the environment is also related to human health, and therefore the assessment of monitoring results for surface water, sediments, and biota may provide important information.

15.6 Evaluating the Contamination

The National Water Law (SEMARNAT, 2004) establishes that the quality requirements of water depends on its use and that human consumption has priority over other uses. TPBS are contaminants that may affect water quality since they are slowly degradable in the environment. They may be transported over long distances, and they tend to bioaccumulate. These substances can cause reproductive and growth problems and other harmful effects in humans and biota. It is also suspected that many TPBS are carcinogens. All these effects caused by TPBS are of concern in Mexico and elsewhere (Fernández-Bremauntz et al., 2004).

Table 15.4: Proposed Environmental Matrixes for TPBS Monitoring**. Source:** Hansen et al., 2006).

Ranking	Human health	Environment
1	Food	Sediments
2	Water for human consumption	Surface water
3	Human biomonitoring	Biota
4	Air	Air
5	Surface water	Water for human consumption
6	Sediments	Human biomonitoring
7	Biota	Food

According to Mexican water-related norms and criteria, the following uses of water consider TPBS limits and criteria:

Water for use and human consumption. The Mexican Health Ministry includes in NOM-127-SSA1-1994 (SSA, 2000) "Environmental Health, Water for Use and Human Consumption – Permissible Limits for Quality and Purification of Water" and in NOM-179-SSA1-1998 (SSA, 2001) "Monitoring and Evaluation of Water Quality Control for Use and Human Consumption, Distributed by Public Supply Systems", limits for three TPBS metals (cadmium, mercury and lead) and nine organochlorine pesticides (aldrin, chlordane, dieldrin, DDT, lindane, hexachlorobenzene, heptachlor, heptachlor epoxide, and metoxychlor).

Control and preservation of water bodies. The Mexican Ministry of the Environment includes in NOM-001-SEMARNAT-1996 (SEMARNAP, 1997) "Maximum Permissible Limits in Wastewater Discharges to Waters and National Properties", in NOM-002-SEMARNAT-1996 (SEMARNAP, 1998a) "Maximum Permissible Limits in Wastewater Discharges to Urban or Municipal Sewage Systems" and in NOM-003-SEMARNAT-1997 "Maximum Permissible Limits for Contaminants in Treated Wastewater to be Reused in Services to the Public" (SEMARNAP, 1998b), which establish limits for the same three metals (cadmium, mercury, and lead). Depending on the type of discharge and on the conditions of the receiving body of water, CONAGUA may require the control of additional TPBS in the particular discharge conditions (SEMARNAP, 1998a).

In the ecological water quality criteria CE-CCA-001/89, the *Ministry of Social Development* (SEDUE, 1989) includes contaminant limits for source water for potabilization, water for recreation with direct contact, for irrigation, cattle farming, and aquatic life. Among these, limits on use are established for the three metals mentioned, and for the following 24 individual or groups of organic TPBS: acenaphtene, aldrin, PCB, hexachlorocyclohexane, lindane, bis(2-ethylhexyl)phthalate (DEHP), 4-bromphenyl ether; chlordane, DDT and metabolites, dichlorobenzene, dieldrin, endosulfan, endrin, fluoranthene, heptachlor, hexachlorobenzene, hexachlorobutadiene, hexachloroethane, PAH, metoxichlor, naphthalene, pentachlorophenol, 2,3,7,8 tetrachlorodibenzo-p-dioxin and toxaphene.

The more significant properties of TPBS which allow us to understand their environmental fate are their low solubilities in water, elevated vapour pressures, high octanol-water partition coefficients (K_{ow}), large organic carbon partition coefficients (K_{oc}), and the elevated Henry law constant (K_H).

Due to the high K_{ow} and K_{oc} and low water solubilities, TPBS are mainly associated with organic material and particles suspended in water. The mechanisms of removal of TPBS from the water column include sedimentation and accumulation in sediments. Therefore, it is considered that sediments act as the final destiny of TPBS. Hence, sediments are an excellent environmental matrix for monitoring:

- the historical contamination of TPBS by sampling and analysis of sediment cores; and
- the present TPBS contamination of water bodies through sampling and analysis of recent sediments (those recently accumulated at the water-sediment interface).

The monitoring of sediments is not a common practice in Mexico and it has not yet been decided who is in charge of controlling sediment quality. Considering the responsibilities of CONAGUA as part of the *Mexican Ministry of the Environment* (SEMARNAT) and since the contamination of the sediments is closely related to water quality, the responsibility for monitoring of the sediments should probably belong to CONAGUA.

Due to their physical properties, in most cases the contamination of soils is limited to restricted geographical regions. Soils are thought to act as secondary sources of contaminants for other environmental matrices such as groundwater, surface water, air, and biota. Also, the distribution of TPBS by atmospheric transport and deposition in terrestrial and aquatic environments can relocate contaminants to broader regions. Few decisions have been made to reduce soil contamination, and evaluation has been mostly investigative or aimed at defining remedial actions. Therefore, long-term surveillance programmes for soil quality are non-existent in Mexico.

Soil surveillance monitoring programmes are also non-existent in Mexico. The responsibility for monitoring soil and dangerous goods belongs to the *General Directorate for Integral Management of Materials and Dangerous Activities* (DGGIMAR) of SEMARNAT. DGGIMAR works together with the *Federal Commission for Protection against Sanitary Risks* (COFEPRIS) in the evaluation of risks and with the *Federal Attorney for Environmental Protection* (PROFEPA) in the remediation of contaminated soil.

The monitoring of TPBS in aquatic flora and fauna may have the following objectives:

- biological indicators of water pollution;

- contamination of fish for the protection of consumers (food);
- protection of individual species and ecosystems.

In Mexico, no norms or other regulations exist for aquatic flora and fauna. NOM-004-ZOO-1994 (SAGARPA, 2001) controls the concentration of 14 individual or groups of TPBS (aldrin, dieldrin, cadmium, chloropyrifos, DDT, endosulfan, endrin, hexachlorocyclohexane, heptachlor/heptachlor epoxide, lead, lindane, mercury, metoxychlor, and PCBs in food from animal sources.

15.7 Modelling

There are at least three reasons to construct and use mathematical models to describe the behaviour of contaminants in hydrological river basins (Schnorr, 1996):

- to understand the transport and fate of these substances through information about their movement, reactions, and transformations;
- to determine how aquatic organisms and humans are exposed to contaminants; and
- to predict future scenarios for contaminant discharges and alternatives for the management of contaminant sources.

To select the most appropriate model, specific objectives must be defined for each case. The complexity of the system must be identified and the questions to be answered by means of the model need to be understood. To construct and apply mathematical models in the description of the fate, adverse effects, and migration of contaminants in hydrological river basins, it is necessary to have adequate field data (concentrations and loads), mathematical formulations, velocity constants or equilibrium coefficients, and criteria for the precision required of the model.

Before using a mathematical model to simulate the effects and the fate of contaminants in hydrological river basins, it is necessary to calibrate, verify, and validate the model. The calibration of a model is a statistically acceptable comparison between the results of modelling and measurements in the field. The acceptance criteria for calibration must be defined in advance, and these depend on the use of the results of the model. The verification of the model is a statistically acceptable comparison between the model results and a data set different from the one used for calibration. To verify the model, coefficients and velocity constants should be the same as those obtained in the calibration. The verification of the model guarantees confidence in its predictive results.

Validation is a scientifically acceptable approval of the model that includes and describes the correct formulation of the most important processes involved in the event studied. That a model is validated implies that it works well in different situations and on several sites. Normally, the validation of a model is a gradual process in which its usefulness is defined by comparing its original predictions with periodic field measurements to determine its accuracy. A model is robust if it is useful in numerous applications, under different situations, and in various study areas.

15.7.1 National Priorities from an International Perspective

In this section, the main international treaties are described as well as activities carried out in Mexico for the evaluation and control of TPBS, are reviewed.

15.7.2 The Basel Convention

The Basel Convention for the control of transboundary movements of hazardous wastes was adopted in 1989 in Basel, Switzerland. This treaty strictly regulates the transboundary movements of hazardous wastes and dictates obligations to its parties to assure that dangerous residues are handled and eliminated in environmentally safe ways. The main points of this agreement establish the following (UNEP, 1989; INE, 2003):

- The production of hazardous wastes must be reduced to a minimum.
- Hazardous wastes must be managed and eliminated at the closest possible point to their source of generation.
- Transboundary movements of hazardous wastes must be environmentally safe.

Mexico signed the agreement in 1989 and ratified it in 1991 (INE, 2003). The Basel Convention came into force in 1992.

15.7.3 The Rotterdam Convention

The Rotterdam Convention focuses on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade. It was adopted in September 1998 in Rotterdam, The Netherlands, as an answer to the growth in the production and commerce of chemical substances during the previous three decades, which had resulted in increased risks associated with the international trade of these chemical substances and pesticides (Fernández-Bremauntz et al., 2004).

In 1980 the *United Nations Environmental Programme* (UNEP) and *the Food and Agriculture Organization* (FAO) developed voluntary programmes for the exchange of information on the commerce of dangerous chemical substances. In 1996 the FAO elaborated and put in practice an International Code of Conduct on the Distribution and Use of Pesticides. This mechanism, denominated Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, is aimed at limiting the exports of dangerous chemical substances and pesticides from developed to developing countries. It was later decided to create an Intergovernmental Committee of Negotiation, which prepared a legally binding instrument that resulted in the Rotterdam Convention. This agreement came into force in 2004 with 73 member states and 128 signatory countries and organizations. The membership is currently made up of 141 countries and organizations. Mexico has neither signed nor ratified this instrument; rather, it has remained an observer (UNEP-FAO, 2009).

15.7.4 The Stockholm Convention

In May 2001, 127 countries adopted a United Nations treaty to ban or reduce the use of of the most toxic substances, considered causes of cancer and congenital defects in humans and animals. The initial 12 POPs subject to this agreement include nine pesticides (aldrin, chlordane, DDT, dieldrin, endrine, heptachloro, hexachlorobenzene, mirex, and toxaphene), one group of industrial products (PCB), and two groups of by-products from various combustion processes (dioxins and furans).

The objective of the Stockholm Convention is to eliminate or restrict the production and use of intentionally produced POPs and to reduce the generation of non-intentional POPs, like dioxins and furans. The Stockholm Convention came into force in May 2004 with 151 signatory countries and 76 member states. Mexico signed the agreement in May 2001 and ratified it in February 2003 (Fernández-Bremauntz et al., 2004).

15.7.5 The North American Commission for Environmental Cooperation

In 1995, Canada, the United States, and Mexico, as member states of the *North American Commission for Environmental Cooperation* (NACEC), created the working group on *Sound Management of Chemicals* (SMOC) in order to establish mechanisms of regional cooperation in the sound management of chemical substances. SMOC considers measures for reduction of sources as well as for prevention and control of pollution, especially for toxic and persistent contaminants.

Six *North American Regional Action Plans* (NARAP) were developed for the management of individual or groups of chemical substances of interest to these three countries: DDT; chlordane; PCB, mercury; lindane; dioxins, furans and hexachlorobenzene. As a result, the requirement to develop research programmes for monitoring and modelling of TPBS was identified, allowing for the detection and evaluation of implications for human health and the environment, with special emphasis on the protection of children's health (Fernández-Bremauntz et al., 2004). In 1999, NACEC established directives to develop a NARAP on *Environmental Monitoring and Assessment* (EMA) that supported the activities of the previous NARAP but also aimed at identifying other TPBS among the other POPs as well as emerging TPBS.

15.7.6 PRONAME and Other Monitoring Programmes

Among the commitments acquired by Mexico as a member of NACEC for the development of EMA was the development of a *National Plan of Environmental Monitoring and Evaluation* (PLANAME) that would identify specific requirements for appropriate decision-making for the characterization and prognosis of the environmental situation in Mexico related to TPBS. In 2005, PLANAME became the *National Program of Environmental Monitoring and Evaluation* (PRONAME), which has as an objective the improvement of the achievement and quality of TPBS monitoring activities in Mexico (INE, 2007).

The strategy for defining and implementing an appropriate monitoring network depends on specific scientific and technical criteria and on the economic situation, as well as on the infrastructure and environmental policies of each country.

Whereas in the USA and Canada the priorities are to develop monitoring strategies for TPBS in various environmental media, through guiding, planning and coordinating existing monitoring programmes (USEPA, 2008), the European Community defined a new strategy of monitoring for the member states that also includes TPBS (European Parliament, 2000).

The questions that should be answered by monitoring and modelling of TPBS in hydrological systems are:

- What are the concentrations of TPBS in water, sediments and aquatic life?
- What are their geographical distributions?
- What are the tendencies in time and distribution of TPBS?
- What are the local, regional, and global sources of TPBS?
- How are they transported?
- Where and how are they accumulated?
- What is their persistence?
- Do they produce chronic effects on humans or on the biota?
- What are the risks of environmental exposure and for human health?
- What are the environmental and health impacts?

To answer these questions for aqueous systems, the hydrological river basin is the recommended study unit, and for Mexico, the infrastructure of the RNM (CONAGUA, 2008b) could function as an excellent base for including TPBS in the list of parameters to be monitored.

15.8 Case Study

With the construction of a dam that will receive water from the Verde and Santiago rivers (figure 15.3) and supply the *Guadalajara urban zone* (ZCG) with 10.5 m^3 s^{-1} for 30 years, over-exploited water supplies such as groundwater and Lake Chapala will be protected. As part of this project, wastewater will be collected and treated throughout the river basins, including wastewater produced in the ZCG. Treated wastewater from ZCG will be returned to the Santiago River downstream from the dam (CEAS, 2006).

Hansen and González Márquez (2010a) reported the results and evaluation of TPBS sampling in water and sediments from the Santiago River. They found that manganese, nickel, copper, and zinc in sediments from the Santiago River showed increasing accumulation with time, while concentrations of arsenic declined, and other metals remained without variation over the past four decades. Concentrations of manganese and nickel in sediments exceeded the Canadian criteria of probable effect on aquatic life (CCME, 2002). In water, the concentrations of nickel were below the ecological criterion for drinking water (SEDUE, 1989).

To evaluate the risk of contaminating water to be stored in the dam, Hansen and González Márquez (2010a) modelled the interaction of contaminants in sediments with overlaying water, simulating varying conditions in the range from aerobic to anaerobic, and sediment re-suspension that may occur during storm flow. The results suggest that manganese concentrations can exceed the limit of the ecological criteria for drinking-water supply (SEDUE, 1989). However, this metal as well as aluminium and iron are easily removed during potabilization of surface water sources (Daniels/Mesner, 2005). The results obtained by Hansen and González Márquez (2010a) suggest that by maintaining sediment accumulation low in the dam, contamination with heavy metals during storm-flow re-suspension would not represent a problem. Nevertheless, if sediments of the current quality are accumulated over time, concentrations of some metals may exceed the ecological criteria for source water for potabilization (SEDUE, 1989) during events of sediment re-suspension.

To prevent the eutrophication (excess of nutrients) of water to be stored in the dam, Corzo Juárez (2009) evaluated the loadings of total nitrogen (N_T), and total phosphorus (P_T) by point sources (industrial discharges and collected municipal wastewater with and without treatment), and by dispersed sources (run-off, agriculture, and livestock) in the river basin of the dam (figure 15.4). He also evaluated the loadings of nickel (Ni).

The loadings of these contaminants by dispersed sources were estimated by calculating run-off taking into account information on precipitation in the region (IMTA, 2005) and the hydrometric information obtained for the rivers (CONAGUA-IMTA, 2007). Average contaminant concentrations in run-off were obtained from Benaman et al. (1996) and Saunders and Maidment (1996). For loadings due to livestock, manure produced was estimated by considering the type of stock (INEGI, 2008) and the concentrations of contaminants according to their weight and purpose of production (Taiganides et al., 1996; Jones/Sutton, 2003). The contaminant loadings from point sources were estimated by analysing the inventory provided by the Jalisco State Water Commission (Óscar Prieto, personal communication) and by means of the con-

Figure 15.3: Study area with sampling points. Source: Hansen et al. (2010).

centrations compiled by Jiménez Cisneros (2001), Hansen et al. (1995) and FAO (1992).

These estimates suggest total annual loadings in the river basin of 132,317 t N_T, 56,309 t of P_T and 0.5 t of Ni. Over 90 per cent of these nutrients correspond to livestock production, especially in the river Verde basin. Considering that secondary municipal wastewater treatment plants typically remove 50 per cent of nutrients (Beavers and Tully, 2005), these would eventually eliminate only 3.4 per cent of N_T and 1.7 per cent of P_T in the whole river basin. Therefore, the collection and treatment of municipal wastewater will not be sufficient to prevent the eutrophication of water. It is therefore necessary to control nutrient loadings, especially from livestock. Control actions may include management of the quantity and quality of animal foodstuff and restricted reuse of manure as agricultural fertilizer.

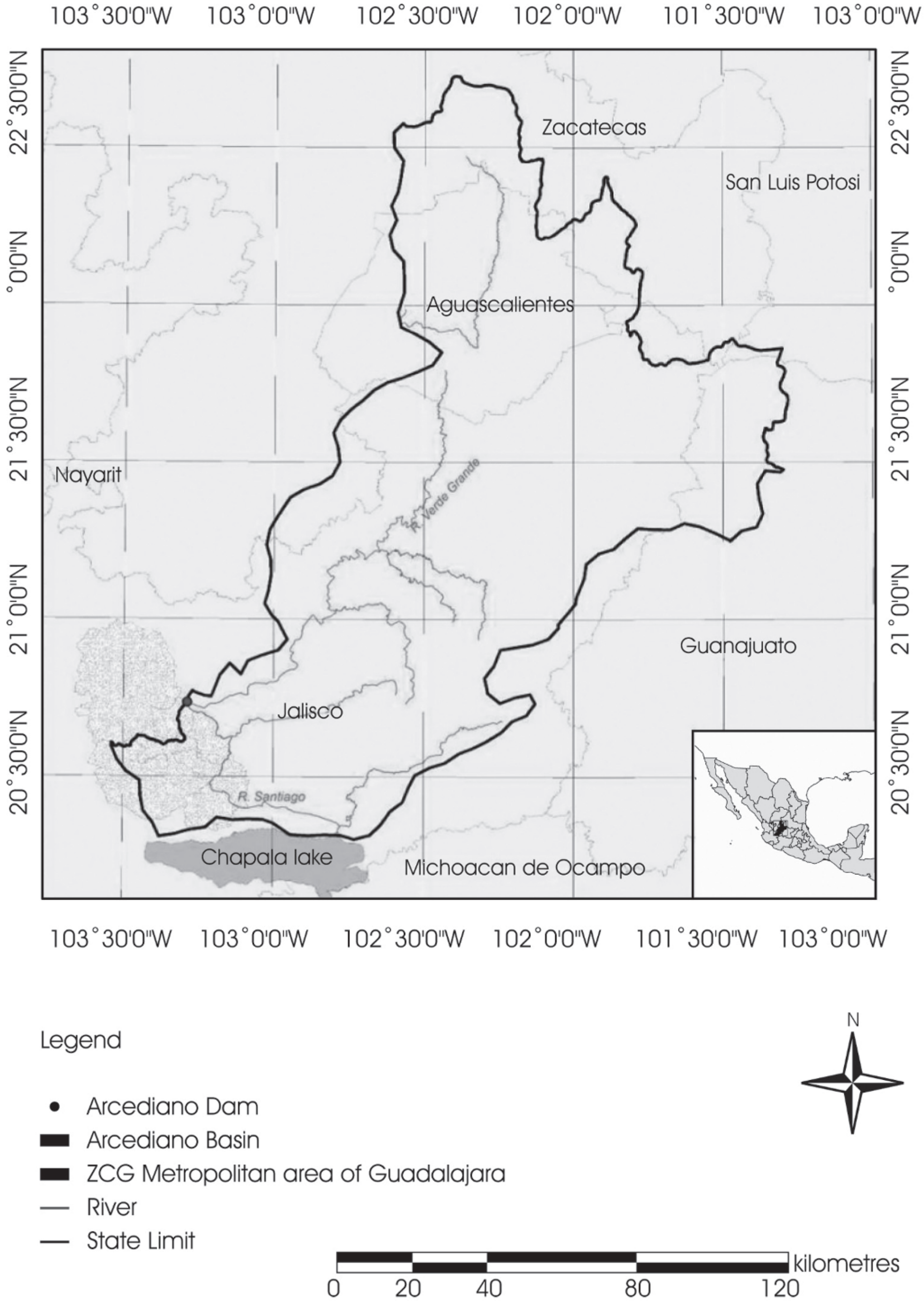
With 70 per cent of the total loadings of Ni, industrial sources in the Santiago River basin are the main sources. It is therefore recommended that an inventory of industrial discharges be made, and pre-treatment systems of wastewater from the industries that discharge this metal be implemented, before incorporating these waters into the municipal sewage treatment plants. This case study demonstrates the importance of considering all the polluting sources in the hydrological river basin, so as to be able to estimate the main source and make the right decisions for solving pollution problems.

15.9 Conclusions

The hydrological river basins provide an adequate reference framework for the development of control strategies for water-related pollution. For the appropriate evaluation of monitoring results of TPBS in hydrological systems, it is recommended that inventories of pollutant sources be made, water and sediments monitored, and contaminant loads evaluated and modelled, as applied to this reference frame.

In order to fulfil international commitments and to protect the health of the environment and the Mexican population, it is essential to implement TPBS

Figure 15.4: Arcediano Dam River Basin**. Source:** Corzo Juárez (2009).



monitoring programmes. Given the lack of TPBS monitoring in Mexico, it is not possible to build on existing programmes. To initiate a programme for the monitoring of TPBS in hydrological river basins, a feasible option is to build on the infrastructure and experience already existing in the RNM (CONAGUA, 2008b).

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16 Water Quality in the State of Aguascalientes and its Effects on the Population's Health

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16.1 Introduction

Aguascalientes is a state located in Central Mexico, with a surface area of 5,589 km^2 (0.3 per cent of Mexican territory; CONAGUA, 2000). Most of the state of Aguascalientes (87 per cent) has a semi-dry climate, with annual average precipitation of 600 mm (rainy season in the summer) and an annual average temperature of 18°C. Some locations in Aguascalientes (13 per cent) have a warm sub-humid climate, with an annual average precipitation of 700 mm, and an annual average temperature of 16°C. The annual average precipitation in the state is 552 mm, with rainfall (80 per cent) predominant between June and September (CONAGUA, 2004).

The total population of the state of Aguascalientes is more than one million. Seventy per cent of the population lives in the capital city and the remaining 30 per cent in ten municipalities. The city of Aguascalientes is a metropolitan area with a population of nearly one million. The main economic activity is in the tertiary sector, commerce, and services, which employ 49 per cent of the *economically active population* (EAP). The second most important economic sector is industry, including textiles, clothing, and automotive and electronic industries, employing 34 per cent of the EAP. The primary sector employs 15 per cent of the EAP (Avelar, 2003a; CONAGUA, 2004).

Aguascalientes has quintupled its population during the last five decades. This population growth has put stress on the demand for natural resources, resulting in non-sustainable growth. Water is the most limited resource in the state of Aguascalientes. Available surface water satisfies only about 20 per cent of the total demand throughout the state. Eighty per cent of the water demand is satisfied from groundwater resources. Water resources to feed the entire population and the industrial and services sectors are then obtained from aquifers. This results in over-exploitation of aquifers, the contamination of surface water bodies by wastewater, and detriment to the quality of groundwater (SARH, 1987; Rodriguez et al., 1997; Avelar, 2003a; Castillo, 2003).

Wastewater is produced at a rate of 103.3 Mm^3/year in the state of Aguascalientes. The municipal, industrial, and other sectors (services, farming and domestic) contribute 95 per cent, 4 per cent and 1 per cent, respectively, of the total wastewater generated in the state. Although the industrial sector generates only 4 per cent of the volume, it contributes nearly 20 per cent to the biochemical oxygen demand (BOD, CONAGUA, 2003).

The basin of the river San Pedro is the most important hydrological system of the state of Aguascalientes. It is confined to the hydrological region Lerma-Santiago. The San Pedro River has an annual discharge of 208 million m^3. This river runs through the state from north to south in a straight line, with a length of 90 km and a drainage surface of 2820.6 km^2. This river is also the main collector of rainfall, wastewater, and treated water. Fifty-six communities are based along the San Pedro River, including six principal municipalities as well as the city of Aguascalientes. Altogether, about 80 per cent of the inhabitants live in these communities. Historically, domestic, industrial, and farming wastes have been discharged into this river basin. For the last 20 years, wastewaters have been treated before they are discharged; however, the installed treatment systems do not remove the stubborn xenobiotics. The river does not have a flow baseline and about 96 per cent (nearly 120 million annual m^3) of treated and un-treated waste waters flow directly to the river. Therefore, the contamination of the San Pedro River constitutes a risk to

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the public health of the communities bordering it, and is a potential source of contamination to the aquifer of the Aguascalientes valley (CONAGUA, 2007). State authorities have set the knowledge of the current degree of environmental quality of this river and its planned remediation as a high priority (SEDUE, 1999; SEMARNAP, 1999; CONAGUA, 2004; CONAGUA, 2005, INAGUA, 2005).

The state of Aguascalientes has five aquifers: the valley of Aguascalientes, the valley of Chicalote, the valley of Calvillo, the valley of Venadero, and El Llano. The valley of Aguascalientes is by far the most important aquifer. The last two aquifers are the least important as far as potential and exploitation are concerned (INEGI, 1993). Groundwater is extracted from 2,846 wells with a total extraction of 556 Mm^3. Extracted groundwater is used in the following activities: 70.1 per cent (390.0 Mm^3) for agriculture, 3.6 per cent (19.8 Mm^3) for cattle, 22.3 per cent (124.0 Mm^3) for urban public use, 2.4 per cent (13.4 Mm^3) for industry and services, and 1.6 per cent (8.8 Mm^3) for other industries (CONAGUA, 2000, 2003).

Following the trajectory of the main trench of the river San Pedro, the aquifer of the Aguascalientes valley is the main source of potable water for the state. This semi-confined aquifer occupies a surface area of 1250 km^2. It provides nearly 80 per cent of the water resources and satisfies 65 per cent of the farming demand and almost 100 per cent of urban and industrial consumption (Avelar, 2003a). During the last three decades, the aquifer of the Aguascalientes valley has been completely over-exploited. The average abatement of the static levels is greater than 2 m annually and exceeds 4 m annually in the city of Aguascalientes (Castillo, 2003). This over-exploitation has created a change in the direction of the water flow and a cracking caused by subsidence, increasing the possibility of infiltration of contaminants into the aquifer (SEDUE, 1999). For the last two decades the sustainable use and protection of water sources has been clearly recognized as a vital priority in guaranteeing the development of the state in the long term (SARH, 1987).

This 10-year study summarizes the main results conducted by our research group on water resource issues in the state of Aguascalientes.

16.2 Objectives

The objectives of this chapter are twofold: a) to summarize and analyse groundwater issues in the state of Aguascalientes and bordering zones, and b) to evaluate the effects of the presence of xenobiotic compounds in the water supplies on the health of the population.

16.3 Methodology

An analysis of the quality of the groundwater in the states of Aguascalientes and South Zacatecas, and of surface waters, groundwater and sediments in the San Pedro river basin were conducted in this study. Procedures for the selection of sampling sites, sampling, sample preservation and the final analysis were conducted following international criteria (USEPA, 1993) and applicable Mexican official norms (NOM NMX-AA-042-1987, NOM NMX-AA-051-SCFI-2001, NOM NMX-AA-115-SCFI-2001, NOM NMX-AA-132-SCFI-2006, NOM-001-ECOL-1996, NOM-127-SSA1-1994). Risk evaluation studies were conducted according to ATSDR-USDHHS-CPEHS-OPS-OMS-UASLP (1992).

16.4 The San Pedro River Basin

Sampling sites were selected in collaboration with the *Institute of the Environment of the State of Aguascalientes* (IMAE), the *Institute of Water of the State of Aguascalientes* (INAGUA), the state delegation of the National Commission of Water, and the municipal operating organisms. Seventy-three sampling sites along the trench of the river San Pedro were selected, taking into account topographical, geological, and hydrological factors, besides relevant points of unloading of polluting agents to the river. In addition, 17 water wells adjacent (less than 300 m) to the trench of the river were also selected. Seven sampling stations were selected in the El Niagara dam, which is the final collector of the river. This selection was based on the morphology and size of the dam (Chapman, 1996). The geographic position of all the sampling sites was determined with a GPS (Garmin, model GPS MAP 60c). Four samplings were made: two during the time of drought (May–June) and two after the rainy season (September–November). Water samples and sediments were taken at point sampling sites on the San Pedro River. Sediment sampling was conducted by random selection at the surface and at 10 cm depth (EPA, 1993). Well water was collected in the pumping stations, after disconnecting the chlorination mechanism and bleeding the system for 15 minutes. The water samples of the El Niagara dam were taken at two depths (at one metre depth and at the mean depth).

Sampling and sample preservation procedures followed Standard Methods (Clesceri et al., 1998; APHA-AWWA-WEF, 2005).

Sediment samples were submitted to a lixiviometric treatment using the Robledo and Maldonado (1997) modified method. The sediments were dried at 50°C for 72 h, homogenized in a porcelain mortar with a wooden mallet, and screened in a 1.0 mm mesh. Five grammes of treated sample were added to 800 ml of distilled water to obtain the extracts. The mixture was stirred for 24 h and filtered. Extracts pH, COD, nutrients and organic toxics were then measured. Heavy metal determination was followed using the methods approved by EPA (1991) and the reference material RM 8704 (Buffalo River Sediments) of the U.S. *National Institute of Standards and Technology* (NIST).

The water quality of the El Niagara dam was evaluated with the *Water Quality Index* (WQI) developed by Dinius and modified by the SEDUE (Guzman, 1997). The *allowed maximum limits* (AML) published in the Mexican official norms: NOM-001-ECOL-1996, NOM-003-ECOL-1997 and NOM-127-SSA1-1994, the quality of ecological criteria of the water (CE-CCA-001-89) for agricultural use (SEMARNAT, 1989) and the values indicated by EPA (1977) for sediments were used as references.

16.4.1 Groundwater Quality

The well water was collected in the pumping stations, after disconnecting the chlorination mechanism and bleeding the system for 15 minutes. The analytical determinations were carried out in agreement with the accepted international protocols (Clesceri et al., 1998).

16.4.2 Analytical Analysis

Measurement of the pH (method 4500-H+ B), conductivity (method 2510 B) and dissolved oxygen (method 4500-O G) were conducted in the sampling sites. The analysis made of water samples included BOD_5 (5210 B), COD by the closed reflux colorimetric method (5220 D), total nitrogen (N_T) by micro-Kjeldahl (4500-Norg B), total phosphorus (Pt) by the ascorbic acid method (4500-P E), detergents like methylene blue active substances (MBAS, 5540 C), phenols by the 4-aminoantipirine method with chloroformic extraction (5530 C), anilines by the colorimetric method of Hess et al. (1993), and the faecal coliforms by the MPN method (9221 C). The fluorides were quantified by the electrometric method. The presence of metals in the water, soils, sediments, and urine and blood samples was quantified with an atomic absorption spectrometer (Perkin Elmer Analyst 100). Graphite furnace (3113 B) or flame (3111 B) was used to determine Al, Cd, Cr, Cu, Fe, Mn, Pb and Zn. Samples were concentrated 10 times during the digestion process to increase the method sensitivity in the flame method. Arsenic was measured using hydrides generation (3114 B), and Hg by cold steam (3112 B). Analyses were done in triplicate. A random fortified sample was used in each sample lot (between 85 and 115 per cent of recovery), as well as a random duplicated sample (variation coefficient of less than 15 per cent). Analytical methods were validated using SRM reference materials of the U.S. NIST. Organochloride pesticides were quantified by gas chromatography. All analytical techniques were conducted according to Standard Methods (Clesceri et al., 1998).

Bayer Multistix® 10 SG Ames reactive strips were used to quantify glucose, bilirubins, ketones, proteins, erythrocytes, nitrites, leucocytes, pH, and density in urine samples. Reactive strip readings were carried out using Bayer Clinitek 50. Urinary sediments were obtained by centrifuging 10 ml of urine for 5 minutes at 7,000 rpm. Sediments were observed using a clear-field optical microscope (40X magnification). Epithelial erythrocytes, leucocytes, cells, cylinders and crystals were also determined in the sediment samples. The quality controls of the general urine examination were followed according to the criteria of Ames Bayer.

A Jaffé kinetic spectrophotometric method was used to determine urine creatinine. 100 µl of urine diluted in distilled water in a proportion 1:50 was mixed with equal parts of a buffer solution (500 µl) and picric acid (500 µl). The spectrophotometer absorbance to 505 nm was recorded.

16.4.3 Risk Assessment by Exposure to Fluorides

An exposed population (n = 188) was selected from the El Llano municipality, where all of the wells exceed the MPL set by NOM-127-SSA1-1994, with an average fluoride concentration of 3.76 mg/l. The control population (n = 140) was selected from the Tepezala and Asientos municipalities (<1.0 mg/l fluoride concentration in the provision of water). Socio-economic food and hygiene customs in both populations (control and exposed) were similar. The selection criteria were young minors of 14 years, born in the community and/or with a minimum time of residence of six years, with water consumption from these wells. The exclusion criteria in both populations were those children with renal and hepatic diseases antecedents. Selected individuals from the above municipalities answered a clinical questionnaire and were submitted to clinical and dental evaluations. An exposure questionnaire was also used to determine other potential sources of exposure to fluorides. Samples of the first urine in the morning were taken to determine fluorides and creatinine. The concentration of fluorides in drinking water and urine was determined using the method 8308 (ion selective electrode), recommended by NIOSH (Tolos, 1994).

16.4.4 Hydroarsenicosis Study

Two regions were studied: the municipalities of Asientos, Tepezala, Cosio, San Francisco de los Romo and El Llano in the state of Aguascalientes, and Ojocaliente, Loreto, Ciudad Cuauhtemoc, Noria de los Angeles, Villa Gonzalez Ortega, Luis Moya, Villa Garcia and Pinos in the state of Zacatecas. Arsenic concentration was determined in 197 water wells in those municipalities.

In the risk assessment study three communities from the state of Zacatecas with major concentrations of As in their drinking water supplies: Ejido Hidalgo, Sauceda de Mulatos and Berriozabal (180, 140 and 94 μg/l As, respectively) were chosen as the exposed population. The control population was selected from the communities of Crisostomos and Tlacotes (with 3.9 and 6.6 μg/l arsenic in drinking water, respectively). These communities presented similar socio-economic levels, productive activities (mainly farming), and nutritional habits. The criteria of inclusion in both populations were females and males, 20 years or older with a minimum period of residence in the community of 15 years and who used tap water as the main source of ingestion of liquids. The exclusion criteria were metabolic illnesses, hepatic and degenerative chronic diseases, and people with a work history in mining zones or labour exposure to arsenic.

Clinical and dermatological exposure surveys and evaluations were applied to both populations (Cebrian et al., 1983). The urine sample collection was followed using the ATSDR (2000) criteria. The first urine of the day was preserved with HCl and stored under refrigeration at 4°C. The creatinine determination and the general urine examination were made on the same day as the sample collection.

The minimum sample size (107 people) was used following the stratified method with a proportional assignation. The real sample size was of 146 and 123 people in the exposed and control populations respectively. Comparative statistical analysis (variance analysis) between the exposed and control populations was conducted. In addition, correlation analyses were also conducted between levels of arsenic exposure, urinary excretion of metalloid, parameters of the general urine examination, and prevalence of keratosis palmoplantaris. The χ^2 test was carried out to compare the prevalence of abortions. The statistical analyses were conducted using Statistica 6.0, with 0.01 levels of significance.

16.4.5 Risk Assessment by Lead Exposure

In Tepezala and Asientos, which are located in the north-west of the State of Aguascalientes, the mining industry was one of the main economic activities. For decades, great amounts of mining waste (tailings) have been accumulated in the outdoor environment, which constitute a source of water, soil, and air pollution. A risk assessment (ATSDR, 1992) in children of 8 to 12 years of age, with at least six years of residence in Tepezala and Asientos (exposed population n=139) was carried out to evaluate exposure to lead. A control population from El Llano (n=187) was selected with a similar culture and socio-economic levels to the one from the exposed population.

Lead concentration in drinking water, tailings, and soil (NMX-AA-132-SCFI-2006), and in blood (NOM-199-SSA1-2000), was quantified to evaluate the main routes and magnitude of exposure to lead. Clinical and exposure questionnaires and a clinical evaluation were conducted to determine other potential sources of lead exposure. Adverse effects were measured by means of the activity of the enzyme delta-aminolevulinic dehydratase in blood (ALA-D) and the concentration of delta-aminolevulinic acid in urine (ALA-U; ATSDR, 2000).

The immunological effect to Pb exposure was also studied using an analysis of components related to the humoral and cellular immune response. The control group included 15 children with blood levels of Pb of 3.12 ± 0.54 μg/dl. The exposed group included 14 children who presented blood concentrations of Pb of 11.70 ± 1.6 μg/dl. Lymphocytes CD19+, total CD2+, and sub-populations CD4+ and CD8+ were quantified. Serum immunoglobulin concentration was quantified by radial immune diffusion and electroimmunodiffusion.

The activity of the complementary system, the functional capacity of the humoral and cellular response to the measles immunizing agent, and the test for intradermoreaction to PPD were determined by means of specific antibodies quantification, using the ELISA technique (Martínez, 2001). Exposed and control populations were compared using comparative statistical analysis (variance analysis).

16.5 Study of Indicators of Renal Damage in Populations Exposed to Cd and Pb

The young population is the most susceptible to toxic exposure. The enzymatic systems of biotransformation and detoxification in infants have not been completely developed. Furthermore, infants have enhanced absorption of metals. The groundwater in Aguascalientes has high concentrations of metals; so evidence of early renal damage in children, induced by Cd and Pb exposure in drinking water, was researched using low-cost non-invasive techniques. This study was performed within the framework of the international project: "Impact of the contamination of potable water by heavy metals: cadmium, lead, chromium and nickel in the renal function during perinatal and postnatal development" (Reyes/Poujeol, 2003).

Rural towns of Aguascalientes whose wells displayed concentrations of cadmium and lead near or slightly above the AML established by NOM-127-SSA1-1994 (0.005 mg/l and 0.01 mg/l, for Cd and Pb respectively) were selected as exposed populations. The principal municipality of Tepezala, where drinking water had a lead concentration of 0.0138 mg/l (1.38 times the AML), was selected. The town of La Luz in the municipality of El Llano was also selected, with a water concentration of cadmium of 0.0036 mg/l (72 per cent of the AML). The control population included the town of La Escondida in the municipality of San Francisco de los Romo, where the well presented lead and cadmium concentrations of 0.0054 mg/l and 0.00035 mg/l, respectively (54 per cent of the AML for Pb, and 7 per cent of the AML for Cd). The three selected communities presented similar socio-economic levels and nutritional habits.

The inclusion criteria were elementary school students between 6 and 12 years old and with a minimum time of residence in the community of two years. The number of children was: control population, n=134; population exposed to cadmium, n=86; and population exposed to lead, n=179 (Torres, 2007). Clinical and exposure questionnaires and a clinical evaluation were applied to determine other potential sources of exposure to lead and cadmium.

16.5.1 Statistical Analysis

Hypothesis testing with sampling from populations that do not present the normal distribution was performed using the central limit theorem (sample magnitude >30). This test determined the significance level between the averages of the urinary excretion of cadmium and lead in the control and exposed populations.

Hypotheses:

H_0: The averages of the populations are equal ($\mu 1 = \mu 2$).

H_A: The averages of the populations are different ($\mu 1\ \mu 2$).

$\alpha = 0.05$

The statistical test is:

$$z = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)_0}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}}$$

Decision rule: Reject H_0 if the value of p obtained with the statistical test is < 0.05.

16.5.2 General Urine Examination

Chi-squared (χ^2) tests were performed using contingency tables with a level of significance (α) of 0.05 (Milton/Tsokas, 1993). These tests determined if the exposure of these three populations to lead and cadmium in drinking water had any relationship to the number of observed positive cases of the different parameters analyzed with the general urine examination. The chi-squared test is used to prove the null hypothesis (H_0). It indicates that two criteria of the classification are independent when they are applied to the same set of organizations. In accordance with both criteria, the classification is represented by means of a table, in which the rows r represent the levels of one of the classification criteria, and the columns c represent the levels of the second criterion. This table is known as a contingency table (Milton/Tsokas, 1993; Daniel, 1997). Both statistical analyses were carried out using Microsoft Office Excel version 2003.

16.6 Results

16.6.1 San Pedro River Basin

Over 350 wastewater and treated water discharge points to the river were documented all along the basin of the San Pedro River and its main affluents. The majority of these discharge points were not registered and the environmental authorities did not know of their existence. Seventy-three sampling sites along the trench of the river and its main affluents were selected. Site selection was conducted based on the released volume to the river and its origin. Four field sampling campaigns were conducted: two during the dry season and two after the rainy season. Results clearly revealed that in spite of the wastewater treatment infrastructure installed in the two last decades, the organic matter, nutrients (phosphorus and nitrogen), and faecal pathogens continue to be the main contaminants of the San Pedro River (Avelar, 2009).

BOD and TSS values in 60 per cent of the water samples exceeded the *allowed maximum limit* (AML) established by NOM-001-ECOL-1996 (150 mg BOD/l and 200 mg TSS/l). Fats and oils were exceeded in 70 per cent of the samples based on the AML (25 mg/l, Avelar 2006). Almost 90 per cent of the water samples exceeded the AML for total nitrogen (40 mg N/l), and 20 per cent exceeded the AML (20 mg P/l) for total phosphorus (Avelar, 2006). Faecal contamination was observed in all the sampling points. The total and faecal coliforms were between 100 and 10,000 times greater than the AML (1000 coliforms MPN/100 ml) established by NOM-003-ECOL-1997 (Avelar, 2009).

Phenols and chlorinated organic compounds (endrin, aldrin, dieldrin and hexachlorobenzene) were not measured in significant concentrations in all samples. By contrast, concentrations of detergents (MBAS) and aniline greater than 20 mg/l were measured in 80 per cent of the water samples. This is considered as a toxic level (Avelar, 2009).

With respect to the heavy metal concentrations, 5 per cent of the water samples had levels of mercury and chromium greater than the AML set by NOM-001-ECOL-1996 (0.02 mg Hg/l and 0.1 mg Cr/l). More than 90 per cent of the samples presented concentrations of aluminium greater than the typical values reported by Metcalf & Eddy (2000) for wastewater (0.1 mg Al/l), and almost 15 per cent exceeded 4 mg Al/l. 13 per cent of the samples exceeded the typical values of manganese (0.2 mg/l) for wastewater. Copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), and lead (Pb) concentrations did not have significantly high levels in the water samples analyzed (Avelar, 2006).

More than 96 per cent of these samples presented acute toxicity for *Daphnia magna* and *Lecane quadridentata* (Ramirez et al., 2007; Avelar, 2009; Rico-Martínez et al., 2000), which is consistent with the high concentrations of organic pollutants and metals observed.

Heavy metals such as Hg, As, Zn, and Cu were the main contaminants in soil and sediments of the trench of the river San Pedro and its main affluents. More than 50 per cent of the samples had concentrations higher than the maximum values as recommended by USEPA (1997) and OMEE (1992). In decreasing order of importance of pollution magnitude, it was found that Pb was the most significant (16 per cent), followed by Cr (9 per cent), Mn (6 per cent), Cd (6 per cent), and Fe (3 per cent). With respect to the organic polluting agents and the nutrients in soil and sediments, generally they were consistent with the results obtained in the water samples (Avelar, 2009).

Although no significant correlation was observed between the contaminant concentrations in the water samples and sediments, the levels of organic matter, inorganic nutrients, and organic xenobiotics were high in both matrices. It is probable that the high content of organic matter and detergents observed in the sediments contribute to the adsorption of heavy metals, increasing the concentration of these xenobiotics in the sediments (Seoanez, 1999), and consequently diminishing their content in the water samples. On the other hand, to a great extent the pH controls the mobility of heavy metals. Values of pH were above 7.0 in all the sediments. As reported in Petrovich et al. (1999), values of pH > 6.0 and high levels of organic matter and detergents, similar to this study, are combined with the argillaceous texture of the soil. They keep the activity of metallic ions in water low, thus remaining almost totally adsorbed, fixed, and precipitated in sediments.

The high concentrations of arsenic in the trench sediments and wells suggest that this metal is mainly of geogenic origin (Gutierrez et al., 2007). This agrees with the high concentrations of arsenic observed in wells located in the north zone of the state (Martínez, 2006).

The water quality of the El Niagara dam, which is the final collector of the river, clearly shows the overall quality of the San Pedro River and the efficiency of the main wastewater treatment plants that discharge to the river. The overall *Water Quality Index* (WQI) of El Niagara puts this water body in the category of 'contaminated' to 'very contaminated' water sources. The highest heavy metal concentrations were Al and Fe. This agrees with the concentrations observed in the samples of water and sediments from the trench. The concentrations of these metals did not exceed the AML established by CE-CCA-001-89 for agricultural irrigation. Even though the water of El Niagara is used for irrigation in the bordering zones and areas of cultivation located downstream, its pollution level means it is not useful because of its content of microorganisms of faecal origin.

There was no evidence of groundwater contamination of anthropogenic origin. Nevertheless, due to the high degree of contamination of the San Pedro River, it represents without a doubt a permanent risk of contamination of the aquifer, the main potable water source in the state of Aguascalientes (Avelar, 2009).

16.6.2 Groundwater Quality

The first reports on groundwater quality in Aguascalientes are somewhat contradictory. Rodriguez et al. (1997) reported high concentrations of lead, phosphates and fats and oils, this last being an indicator of the anthropogenic origin of pollution. By contrast, Hansen et al. (1997) reported high levels of fluorides, phosphates and ammoniac nitrogen.

A study conducted by our group, in which groundwater was assessed in 60 wells from 10 municipalities in the state, found that groundwater had fluoride, arsenic, mercury, chromium, iron, manganese, and lead concentrations higher than the AML set by NOM-127-SSA1-1994. These findings differ from the results of previous studies. In our study, high concentrations of fluorides were found in the municipalities of Calvillo, Cosio, Jesus Maria, Rincon de Romos, San Jose de Gracia, and El Llano. A significant number of wells with high concentration of arsenic were also noted in the municipalities of Asientos, Cosio, and Tepezala, located in the north of the state. These arsenic concentrations were at or above the AML set by the NOM. Elevated levels of salinity and low values of pH (< 6.5) were also very frequent in wells in all parts of the state (Avelar/Llamas, 2000).

One hundred and seventy-eight wells provide water to the population in the municipality of Aguascalientes. A systematic monitoring (31 parameters by well, twice a year) was conducted between 1995 and 2001. The problem in the aquifer of the Aguascalientes valley (Castillo, 2003) was found to be high concentrations of fluorides, mercury, phenols, lead, and ammoniac nitrogen (exceeding the AML set by NOM-127-SSA1-1994). The high concentration of fluorides in the water of the aquifer of the Aguascalientes valley was the most important issue. Forty-two per cent of wells in the municipality of Aguascalientes had concentrations of fluorides greater than 2.0 mg/l (the AML set by the NOM is 1.5 mg/l), which implies that an approximate population of 360,000 inhabitants is exposed to non-recommendable levels of this substance. The highest concentration of fluorides was 7 mg/l (Castillo, 2003). Mercury concentrations higher than the AML set by the NOM (0.001 mg/l) were observed in 26.7 per cent of the wells in the municipality of Aguascalientes. Only 0.6 per cent of the wells presented concentrations equal to or greater than 0.002 mg/l, that is, double the AML. In accordance with these results, more than 200,000 inhabitants would be exposed to mercury levels near the AML set by the NOM, and approximately 5,000 inhabitants would be exposed to concentrations twice as high as this AML. With respect to lead, 37 per cent of wells presented concentrations greater than the AML set by the NOM (0.01 mg/l). Approximately 294,000 inhabitants could be exposed to non-recommended levels of lead (Castillo, 2003).

16.8 per cent of the wells in the municipality of Aguascalientes had concentrations of phenols greater than the AML set by the NOM (0.001 mg/l), which implies an approximate population of 145,000 inhabitants exposed to non-recommended phenol levels. 8.5 per cent of the wells in the municipality of Aguascalientes showed levels of ammoniac nitrogen higher than the AML set by the NOM (0.50 mg/l). Since the ammoniac nitrogen present in the water of the aquifers is normally produced by microbial degradation of organic matter, these last results evidence a probable contamination of the aquifer by organic matter, which would imply an interaction between the aquifer and superficial wastewaters (Castillo, 2003).

Important problems of groundwater quality in relation to physico-chemical parameters such as pH, conductivity, hardness, alkalinity, and temperature were observed. Generally, the water of the aquifer tends to present low values of pH. 5.42 per cent of wells presented pH below 6.5 units (the minimum allowed by the NOM). High concentrations of dissolved salts in the aquifers are reflected by high values of conductivity. 46.9 per cent of the wells registered values greater than 600 µSiemens/cm of conductivity. Hardness and alkalinity were usually located between moderate and high levels. Finally, high temperatures were registered frequently. In general, groundwater showed several problems of quality because of a combination of low pH, high conductivity and elevated hardness, high temperature, and the presence of fluorides (Castillo, 2003).

This study also reflected an alarming depression of the aquifer. Between December 1998 and June 2001 an average depression in the static levels of 11.9 m was observed; which means a rate of depression of approximately 40 cm monthly; that is, an annual loss of almost five metres. A previous study indicated an average annual depression of 2 to 4 m. This result implies a substantial increase in the rate of depression of the aquifer during the last few years (Castillo, 2003).

Statistical analysis (almost 30,000 items of data) showed evidence of a correlation between the level of depression of the aquifer and alterations in the groundwater quality. The concentrations of arsenic and manganese, as well as the temperature, showed an increasing tendency in relation to the depression of the aquifer. Groundwater quality in the municipality of Aguascalientes is affected due to the accelerated over-exploitation of the aquifer. Parameters of quality representing significant problems, such as the fluorides, mercury, phenols, and lead, could be exacerbated in the near future (Castillo, 2003).

16.6.3 Risk Assessment by Exposure to Fluorides

Fifty-one per cent of the wells that provide potable water to the population in the state of Aguascalientes had a concentration of fluorides higher than the allowed maximum levels (AML) established by NOM (1.5 mg/l). This problem is especially important in the municipality of El Llano, in which all the wells exceeded the AML set by the NOM (the average concentration was 3.8 mg/l). The exposed population (n=188) included children with a minimum time of residence of 6 years in the municipality of El Llano. The control population (n=140), also children with a minimum time of residence of 6 years, was selected from the municipalities of Tepezala and Asientos, which had a concentration of fluorides in the water supplies lower than 1.0 mg/l. The prevalence of dental fluorosis in the exposed and control populations were more than 60 per cent and less than 20 per cent, respectively. Thus, the high fluoride concentration in the water supplies constitutes the main factor determining the greater incidence of dental fluorosis in the exposed population. The high frequency of caries found in both populations (37 per cent) is explained by the lack of oral hygiene practices (Perez, 2004).

16.6.4 Hydroarsenicosis Study

The study included 197 water wells from the border zone of the inter-state limit between Aguascalientes and Zacatecas. Forty-two communities were found to be exposed to high arsenic concentrations in drinking water, at arsenic concentrations between 2 and 7 times greater than the AML set by the NOM (25 µg/l). These communities included four principal municipalities: Cosio and Tepezala in Aguascalientes, and Ojocaliente and Luis Moya in Zacatecas. The exposed communities represent a population of 95,000 people. In southern Zacatecas, 28 out of the 86 wells analysed had arsenic concentrations higher than the AML established by the NOM.

In northern Aguascalientes, 14 out of the 111 water wells analysed had arsenic concentrations higher than the AML set by the NOM. In the municipality of Cosio, 83 per cent of the water wells studied had high concentrations of this metalloid (Avelar, 2003b; Martínez, 2006). Arsenic pollution in these water wells is more important if the concentrations found are compared with the maximum arsenic concentration in drinking water recommended by the WHO (10 µg/l). Forty-five out of the 111 (40.5 per cent) water wells in northern Aguascalientes exceeded the maximum arsenic concentration recommended by the WHO. Affected municipalities included Cosio, Tepezala, Asientos, and San Francisco de los Romo (Tchounwou et al., 1999; ATSDR, 2000; Avelar, 2003b; Martínez, 2006).

Table 16.1 shows data from the study of arsenic exposure in the control and exposed populations (Berriozabal, Sauceda de Mulatos and Ejido Hidalgo). The daily ingestion of arsenic from drinking water in the exposed communities was 1.5 and 3.5 times higher than the tolerable maximum value recommended by the WHO (2 µg/kg, Tchounwou et al., 1999). A statistical correlation of arsenic concentrations (r^2 = 0,989) in urine and drinking water was observed to be significant. Also highly significant were the differences between the urinary arsenic concentrations in the exposed population (n=146) with respect to the control population (n=123). It is concluded that the main human exposure to arsenic is through drinking water.

Twelve per cent of the exposed individuals (over 20 years of age and with a minimum residence in the community of 15 years) showed an incidence of cutaneous injuries related to arsenical keratosis (palmoplantaris). In addition, a statistically significant corre-

Table 16.1: Exposure to arsenic and adverse effects in control and exposed populations. **Source:** Authors' research results.

Community	Arsenic in drinking water (µg As/l)	Daily ingestion of arsenic (µg As/Kg)	Urinary excretion of arsenic (mg As/mg creatinine)	Population with keratosis palmoplantaris (%)
Control (n = 123)	5	0.2	0.24 ± 0.11	3.2
Berriozabal (n = 55)	94	3.4	2.25 ± 1.3	10.9
Sauceda de Mulatos (n = 20)	140	5.2	3.63 ± 2.0	15.0
Ejido Hidalgo (n = 71)	180	7.5	5.04 ± 2.6	18.3

lation (r^2 = 0.987) was found between the incidence of arsenical keratosis and the level of exposure to arsenic. According to these results, high arsenic levels in drinking water are causing adverse effects on health for a significant percentage of the population chronically exposed (Avelar, 2003b; Flores 2006).

Even though not conclusive, it is speculated that the frequency of abortions was positively correlated with the daily intake of arsenic in drinking water. There was a statistically significant difference between the control population (38 per cent) and the Ejido Hidalgo sample (57 per cent) using a $p < 0.05$. It is an urgent priority that the Health Services Agency should take care of this problem. There was no statistically significant evidence linking the consumption of water contaminated with arsenic and alterations in the parameters determined in the general urine examination.

16.6.5 Risk Assessment by Lead Exposure

Levels of Pb in blood showed a different distribution in the two populations. Highest concentrations of lead were observed in the exposed population, and fourteen samples displayed values between 10 and 16 µg/dl of Pb in blood. With respect to the injury biomarkers, in 139 samples of the exposed population, which presented an overage Pb concentration in blood of 9.35 ± 1.3 µg/dl, a greater urine excretion of ALA-U (amino levulinic acid) and a smaller activity of ALA-D (amino delta levulinic dehydratase) were observed with respect to the control population. The statistical differences in both biomarkers were statistically significant for $p < 0.05$ (Martínez, 2001).

The absolute number of lymphocytes CD19+, CD2+, and CD8+, and the concentrations of immunoglobulins G, M and A, did not show significant differences between the two groups (exposed and control populations). The antigenic challenge with the measles virus did either show significant differences between the two groups, in relation to the levels of specific immunoglobulins M and G. Estimation of the capacity of the cellular response, through the cutaneous test of the PPD (*purified protein derivative*), was also similar in both populations. On the other hand, significant differences ($p < 0.05$) were observed between both groups in the absolute number of lymphocytes CD2+/CD4+ (Martínez, 2001).

16.6.6 Study of Indicators of Renal Damage in Populations Exposed to Cd and Pb

Children exposed to cadmium in La Luz presented an average urinary excretion of Cd four times greater than the control population. This represents a statistically significant difference (p=0.0009) between the two populations. The average urinary excretion of cadmium in the control population (0.31 µg of Cd/g of creatinine) was similar to values typically reported (0.1 to 0.6 µg of Cd/g of creatinine; Jarüp, 2006). In contrast, the exposed population presented an average urinary excretion of cadmium of 1.16 µg of Cd/g of creatinine. With this level of exposure, statistically significant differences were observed (with a level of significance of 1 per cent) in the percentage of positive cases of proteinuria (10.6 per cent), bilirubins (8.23 per cent) and ketones (11.76 per cent) in the exposed population, with respect to the values observed in the control population (0.8 per cent, 0 per cent and 0 per cent for proteinuria, bilirubins and ketones, respectively; Torres, 2007). Early renal effects, like tubular proteinuria, have been reported with urinary cadmium excretions from 2 to 4 µg of Cd/g of creatinine. A three times greater risk of proteinuria was observed in people with cadmium urinary excretion of 1 μg of Cd/g of creatinine (Jarüp, 2006).

Children exposed to lead in Tepezala presented an average urinary excretion of lead 2.5 times greater than in the control population, giving a statistically significant difference (p=0.0000). The average urinary lead excretion in the control population was 10.5 μg of Pb/g of creatinine. By contrast, the exposed population showed a lead excretion of 26 μg of Pb/g of creatinine. With this level of exposure, statistically significant differences were observed (with a level of significance of 1 per cent) in the percentage of positive cases of proteinuria (8.4 per cent), bilirubins (3.4 per cent) and ketones (6.2 per cent) in the exposed population, in contrast with the values observed in the control population (0.8 per cent, 0 per cent and 0 per cent for proteinuria, bilirubins and ketones, respectively; Torres 2007). These results agree with a previous study done by Fels (1998) that observed a urinary excretion of Pb twice as great as the control population, and the presence of indicators of renal damage.

In this study, carried out in infant populations exposed to metals in drinking water, a statistically significant correlation was observed between the levels of exposure to cadmium and lead and the incidence of indicators of renal dysfunction. The cadmium and lead concentrations in the water supplies slightly exceeded the AML set by the World Health Organization (0.003 mg/l and 0.01 mg/l for cadmium and lead respectively; WHO, 1995). The cadmium concentration in the exposed population was lower than the AML (0.005 mg/l) set by NOM-127-SSA1-1994 (Torres, 2007). It is of the greatest importance to follow up the communities studied in order to better establish the risks of exposure to heavy metals in drinking water, even in concentrations considered to be safe.

16.7 Conclusions

The San Pedro River is heavily contaminated with the discharge of domestic and industrial effluents with high concentrations of organic matter, nutrients (total phosphorus and total nitrogen), organic xenobiotics and faecal matter. The sediments reflected the anthropogenic impact on the trench, which has been used as a reservoir of a multitude of residues for decades. The sediments showed high volumes of organic xenobiotics (anilines and detergents), and levels of pollution by Cu and Zn. Besides the anthropogenic impact, an important contamination of natural origin by arsenic was observed. The physico-chemical characteristics observed in the sediments suggest a high capacity for immobilizing metals and organic xenobiotics. The capacity for auto-purification of the San Pedro River is reduced and its contamination constitutes a risk to public health and to its ecological surroundings. The water quality of the Niagara dam is not suitable for irrigation. Evidence of the contamination of the aquifer by the surface water from the San Pedro River was not conclusive.

The main problem of groundwater quality is the high concentrations of fluorides, arsenic, mercury, chromium, iron, manganese, and lead. In the municipality of Aguascalientes, groundwater supplies contaminated with phenols and ammoniac nitrogen were also observed; these results suggest the infiltration of polluting agents into the aquifer of the Aguascalientes valley. Other issues deal with high concentration of salts, low pH and high temperature. There are water wells that frequently combine low pH, elevated conductivity and hardness, high temperature, and fluoride concentrations above the AML. An important increase in the abatement rate of the aquifer of the Aguascalientes valley was observed, reaching 5 m annually. A correlation between the level of abatement of the aquifer and alterations in the quality of the groundwater was observed. Groundwater in the municipality of Aguascalientes is affected by the accelerated over-exploitation of the aquifer. High concentrations of fluorides were found throughout the state of Aguascalientes. High concentrations of arsenic were found in the municipalities of the north near the state of Zacatecas.

The presence of high concentrations of fluorides in the drinking water supply constitutes the main factor determining the greater incidence of dental fluorosis in the exposed populations.

In the municipalities of northern Aguascalientes and southern Zacatecas, 42 communities were found to be exposed to high concentrations of arsenic in drinking water. The evidence suggests that the intake of polluted water constitutes the main exposure pathway of this metalloid. High levels of arsenic in drinking water are having adverse chronic effects on the health of a significant percentage of the exposed population.

In the municipalities of Tepezala and Asientos, high lead concentrations in blood were observed (above to 10 μg/dl). With respect to injury markers, a greater excretion of ALA-U and a smaller activity of ALA-D were observed for the control population. The differences in both biomarkers were statistically significant.

The infant populations that were exposed to metals in drinking water showed a statistically significant correlation among the levels of exposure to cadmium and lead, and the incidence of indicators of renal dysfunction (proteinuria, bilirubins and ketones). The cadmium and lead concentrations in the water supplies were slightly higher than the AML set by the World Health Organization (0.003 mg/l and 0.01 mg/l for cadmium and lead respectively; WHO, 1995). The cadmium concentration in the exposed population was lower than the AML (0.005 mg/l) set by NOM-127-SSA1-1994 (Torres, 2007). A follow-up of the communities studied is of the utmost importance to better establish the risks of exposure to heavy metals in drinking water, even in concentrations considered safe. Further research is needed to determine the effects of xenobiotics in drinking water on the health of the population.

It is very important to be in continuous communication with the appropriate State agencies concerning the health risks of the populations exposed to raised concentrations of xenobiotics and other contaminants in surface water. The effective and immediate intervention of the State authorities is also urgently required, to clean up the polluted surface water bodies and to reduce the consumption of contaminated water, as well as to upgrade the quality of drinking water to acceptable levels. The sustainable use of water resources is the most fundamental challenge facing the state of Aguascalientes. Methods to promote sustainable consumption of water resources include actions such as combating water spills, eliminating subsidies in the price of water supplies (particularly in wealthy colonies), and the use of state-of-the-art technology in the irrigation system of parcels of agricultural land.

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17 Potable Water Pollution with Heavy Metals, Arsenic, and Fluorides and Chronic Kidney Disease in Infant Population of Aguascalientes

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17.1 Introduction[1]

Lack of potable water is an important problem of global dimensions. In Mexico, the northern and central regions have significant shortages, a situation which is exacerbated by the pollution of aquifers. Several studies have reported controversial results on high concentrations of heavy metals and halogens in aquifers in the state of Aguascalientes. Poor water quality is caused by the geological conditions in the region, water over-exploitation, and inadequate disposal of industrial waste. However, human exposure to these xenobiotics and their associated toxicological impact has received minimal attention. Many of these contaminants are nephrotoxic agents and this condition is aggravated when they mix.

In the municipality of Calvillo in Aguascalientes, a high prevalence of *Chronic Kidney Disease* (CKD) has been identified amongst the infant population (almost one hundred times the reports for the population younger than twenty years). This chapter will offer the results of various studies evaluating water quality in Aguascalientes in order to identify the presence of potentially nephrotoxic contaminants in potable water.

Surface and groundwater quality was assessed to find the concentrations of metals, metalloids, and halogens, and to compare them with the standards set by Mexican law (NOM) and by the WHO. Thereafther nephrotoxic effects of some of these chemicals were evaluated using in vivo and in vitro studies. The results presented in this chapter show that despite the treatment of water discharges into rivers, organic waste pollution, inorganic nutrients (nitrogen and phosphorus), and faecal pathogens are the main causes of surface water pollution. Regarding water quality in aquifers, there are differences between different regions. A common problem in most municipalities is the high concentrations of fluorides, followed by mercury and lead, and finally cadmium and chrome in lower quantities. In addition, this research group has developed experimental models to study the possible action mechanism of these compounds and their possible role on CKD. These results show that the pollution of aquifers could fully or partially account for the high prevalence of CKD amongst the infant population of Aguascalientes. This does not establish a causal relationship between this pollution and CKD, but the results presented below provide important information in order to orient future research about his severe health problem.

Scarcity of potable water is an important global problem. According to the *Millennium Development Goals* (MDGs), the population without access to water needs to be reduced by half (Oki/Kanae, 2006). In Mexico, water scarcity is affecting important central and northern regions. The causes of water scarcity are various; they have been addressed by many authors who have stressed: a) pollution of aquifers due to mixed causes (geological conditions and anthropogenic factors); b) insufficient recharge of aquifers due to limited rainfall and over-exploitation; and c) demographic growth.

It is common that aquifers located in volcanic regions such as Aguascalientes present worrying concentrations of heavy metals. Also, demographic growth and industrial development have led to an increasing demand for water. In order to satisfy this demand, wells have been dug at greater depths, reaching fossil waters with high concentrations of metals and

1 Keywords: water, pollution, xenobiotics, heavy metals, fluorides, chronic kidney disease, infant population in Aguascalientes.

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salts. In addition, inadequate disposal of industrial waste has exacerbated the situation, leading to pollution of surface waters and groundwaters. Hence it cannot be stressed too highly that not only is the availability of water crucial, but also water quality is fundamental, since it may bear important consequences for human health. However, the topic of potential human exposure to the toxicity of xenobiotics has received minimal attention.

It is important to stress that a high incidence of CKD has been identified among the infant population of Aguascalientes. Since the year 2002, the state hospital 'Miguel Hidalgo' (a hospital with specialized treatment) has registered an increase in CKD cases in children from the municipality of Calvillo. This fact led to the study of the prevalence and characteristics of CKD in the region. The results have been alarming, with a prevalence of CKD of 700 per 100,000 inhabitants (Góngora Ortega, 2008), representing a hundredfold increase compared with the prevalence of this pathology in the young population of 20 years or less, at 74.7 cases per million (Ardissino et al., 2003). The aetiology of CKD is diverse, and includes factors such as geographical region and genetic and environmental factors (Hari et al., 2003).

This chapter reviews the results of various studies which evaluate water quality in Aguascalientes in order to identify the presence of potentially nephrotoxic contaminants in potable water.

17.2 Methodology

In order to evaluate whether the development of CKD among infant populations is linked –at least partially – to the use of contaminated water, the problem must be addressed through distinct viewpoints. The first is the analysis of water quality in different regions of the state of Aguascalientes, identifying pollution by xenobiotics including heavy metals, metalloids, and fluorides, many of which are nephrotoxic. We compared the concentrations of xenobiotics in water with epidemiological studies reporting renal toxicity effects at similar concentrations. Besides this, we included results of studies with animal and *in vitro* models using the pollutants we identified in order to assess renal damage and its action mechanisms.

It is clear to us that we are still far from establishing a causal relation between these contaminants and the development of CKD, as this would imply including risk impact studies, some of which are currently under way while others have only been proposed and are yet to be conducted. However, we consider that this work provides important information regarding an important regional health challenge in order to guide future research.

17.3 Results relating to Water Resource Problems in Aguascalientes

17.3.1 Surface Water and Water Quality Situation

The state of Aguascalientes represents 0.3 per cent of the national territory, and occupies an area of 5.589 km^2 (CONAGUA, 2000). The total population is estimated at over one million, with 70 per cent concentrated in the capital city and the rest distributed over ten municipalities. Rapid demographic growth has generated tremendous pressure on natural resources, generating an unsustainable exploitation dynamic. Surface water availability only accounts for the needs of 20 per cent of the population, forcing the exploitation of aquifers to meet the remaining 80 per cent of the demand. This condition has generated the over-exploitation of water from aquifers. Additionally, the pollution of the main surface water sources generates poor water quality (SARH, 1987; Rodríguez et al., 1997; González, 2002; Avelar, 2003a; Castillo, 2003).

The basin of the San Pedro river is the most important surface hydrological system in the state of Aguascalientes. The river is the main collector of rainwater and of treated and discharged waters. Fifty-six communities are located on its margins – with a population nearing 800,000 inhabitants – including six municipal districts and the City of Aguascalientes, discharging approximately 75 million m^3 of treated and wastewaters to the river annually. In the past twenty years an increasing proportion of these wastewaters has been treated, although existing treatment systems do not remove persistent or xenobiotic contaminants (SEDUE, 1999; SEMARNAP, 1999; CONAGUA, 2004, 2005; INAGUA, 2005).

A longitudinal study to evaluate water quality in the San Pedro river has systematically inspected water flows in its main course and tributaries (Avelar, 2006), documenting over 350 treated water and wastewater discharge points. Most discharge points were not registered and environmental authorities were unaware of their existence. Data obtained clearly reveal that despite the water treatment infrastructure installed over the past two decades, the main water pollution problems in the San Pedro river are still organic waste, inorganic nutrients (phosphorus and nitrogen), and faecal pathogens, with a lower proportion of chemical contaminants (Avelar, 2006).

17.3.1.1 Aquifers

The state of Aguascalientes has five aquifers: Aguascalientes Valley, Chicalote Valley, Calvillo Valley, Venadero Valley, and El Llano (INEGI, 1993). Groundwater is extracted from 2,846 identified wells, representing a total extraction of 556 mm^3 (CONAGUA, 2000, 2003).

Following the trajectory of the San Pedro river, the Aguascalientes Valley is the main aquifer providing water to the state. It provides nearly 80 per cent of water for all sectors, satisfying 65 per cent of agricultural demand and 100 per cent of urban and industrial water demand (Avelar, 2003a). In the past three decades, the Aguascalientes Valley aquifer has been over-exploited; average abatement of static levels is over 2 m overall per annum, with an annual average of 4 m in the City of Aguascalientes (Castillo, 2003). This level of over-exploitation has caused subsidence and fissures, altering flows and increasing the risk of infiltration of pollutants to the aquifer (SEDUE, 1999).

17.3.1.2 Groundwater Quality

Regarding the water quality in aquifers, findings prove contradictory. In a study of groundwater flows, high concentrations of lead, phosphate, fats, and oils were found. This last element is evidence of the presence of anthropogenic contaminants (Rodríguez et al., 1997). Also, according to an evaluation of wells located in the City of Aguascalientes and the surroundings of the El Niágara dam (Hansen et al., 1997), high concentrations of fluorides, phosphates, and ammoniac nitrogen were reported in groundwater, all of which were above official levels set by national norms (NOM).

In the year 2000, this research team evaluated groundwater quality in the state of Aguascalientes, including 60 wells in 10 municipalities. Results revealed high concentrations of pollutants, above the limits set by the NOM-127-SSA1-1994; such as fluorides, arsenic, mercury, chrome, iron, manganese, and lead. The most alarming results in terms of water quality were fluoride concentrations, given the high number of populations and inhabitants affected. The most affected municipalities were Calvillo, Cosío, Jesús María, Rincón de Romos, San José de Gracia, and El Llano. In addition, an important number of wells reporting high arsenic concentrations were documented in the northern municipalities of the state, such as Asientos, Cosío, and Tepezalá. Besides this, high salinity and low pH levels were found, the latter in most of the state (Avelar/Llamas, 2000).

Based on these results it was assumed that there was a need to systematically monitor 178 wells that provide water to the population of the City of Aguascalientes. We considered 31 parameters per well, measured twice per annum (Castillo, 2003). According to this study, the main problems detected were high concentrations of fluorides, mercury, and lead (all above the levels set by official standard NOM-127-SSA1-1994). Again, high concentrations of fluorides were the most recurrent problems for water quality in the Aguascalientes Valley aquifer. Around 41.7 per cent of wells had fluoride concentrations above 2.0 mg/l; in some wells, 7 mg/l were found – the maximum permissible limit is 1.5 mg/l – implying that approximately 360,000 inhabitants are environmentally exposed to fluorides. Around 26.7 per cent of wells had mercury concentrations above official standards (0.001 mg/l); this means that more than 200,000 inhabitants are exposed to high levels of mercury, and that approximately 5,000 inhabitants are exposed to mercury concentration two times higher than the limits set by official standards. For lead, 25 per cent of wells reported concentrations higher than official standards (0.025 mg/l), implying that nearly 221,000 inhabitants could be exposed. The geological features of the region, together with pollution derived from lixiviates in mine tailings, could possibly explain the high concentration of pollutants found. Nevertheless, over-exploitation of aquifers causing deeper well perforation is also crucial. It has been proved that a correlation exists between aquifer over-exploitation and changes in the quality of groundwater, such as increased concentrations of chemical polluting agents (Castillo, 2003).

Aquifers providing water supply for many municipalities of the state of Aguascalientes have high concentrations of metals, metalloids, and fluorides, above the official standards set for human water consumption. This situation implies an important health risk for environmentally exposed populations.

17.3.2 Water Pollution due to Heavy Metals, Arsenic, Fluorides, and its Relation to Renal Toxicity

17.3.2.1 Fluorides

High fluoride concentrations in water are probably due to geological causes. The geographic region surrounding the state of Zacatecas is known as the 'fluorite belt'; it includes various states in the centre and north of Mexico (Ortega Guerrero, 2009). About 51 per cent of wells providing potable water to the state of Aguascalientes have fluoride concentrations above official standards (NOM at 1.5 mg/l). Exposure to high concentrations of fluorides in potable water is associated with negative effects in human health such as dental and skeletal fluorosis, cancer, and higher risk of renal disease (Connett, 2006). Avelar group conducted a study to estimate dental fluorosis associated with exposure to fluorides in water for domestic use. The sample was made up of toddlers, infants, and children who had lived at least 6 years in the El Llano municipality (where fluoride concentrations in wells were up to 7 mg/l), whereas the selected control population comprised the municipalities of Tepezalá and Asientos (where fluoride concentrations in water were below 1.0 mg/l). Exposure to fluorides was determined by measurements of the xenobiotics in potable water and urine. According to these results obtained, the presence of fluorides in potable water constitutes the factor that determines the highest incidence of dental fluorosis in exposed populations (Pérez et et al., 2004). Liu et al. (2005) reported that exposure to fluorine in drinking water in amounts greater than 2 mg/l is linked to renal disease in infant populations. There are scarce information available about the relationship between fluoride exposure and CKD. This study provides important information, as some sampled wells had fluoride concentrations above 7 mg/l, indicating that possibly fluoride ingestion in potable water has a role to play in the development of renal pathologies in the region. Currently, we are developing animal and in *vitro* model studies in order to evaluate the nephrotoxic effects and action mechanism of this halogen. Preliminary results link acute exposure to fluorides with proteinuria, increased urinary frequency, and tubular dysfunctions (Arreola Mendoza et al., 2009).

17.3.2.2 Arsenic

Besides the geological origin of arsenic, which is part of the chemical structure of more than two hundred minerals, anthropogenic pollution is important. The study of 197 wells supplying water to the population next to the interstate boundary between Aguascalientes and Zacatecas was crucial in identifying 42 communities exposed to high arsenic concentrations in water for human consumption (concentrations between 2 and 7 times the limits set by official legislation at 25 g/l), including the four municipal capitals (Cosío and Tepezalá in Aguascalientes; Ojo Caliente and Luís Moya in Zacatecas). In the 42 communities, the population exposed to arsenic comprised 95,000 people (Avelar 2003b; Martínez 2006). Daily absorption, derived only from potable water, exceeded between 1.5 and 3.5 times the limits set by the WHO (2 μg/kg, Tchounwou et al., 1999). In the communities, the incidence of skin lesions and palmoplantar hyperkeratosis linked to hydroarsenicism was discovered to be 12 per cent of the sample studied (Avelar 2003b; Flores 2006). Besides causing hyperkeratotic lesions, exposure to arsenic has been linked to skin, lung, and bladder cancer, and to alterations in the immune and neurological systems, as well as to mellitus diabetes and hypertension (Rahman et al., 2009). It is imperative to mention that both diabetes and hypertension are two of the most important causes contributing to CKD in the world's adult population.

17.3.2.3 Lead

In the north-eastern region of the state of Aguascalientes, especially in the municipalities of Tepezalá and Asientos, the mining industry was one of the main economic activities. For decades, significant quantities of mine tailings have accumulated in the open, accounting for the pollution of water, soil, and air. As part of the study evaluating health risks, the concentration of lead in blood in the infant population residing near mining areas was measured.

Results show that for the exposed population, lead concentrations in blood were 9.35 ± 1.30 μg/dl, reaching values of up to 16 μg/dl. These values are significantly higher than those found in the control population (3.12 ± 0.54 μg/dl, lower limit of Category I of official law NOM-004-SSA1-1999; Martínez 2001). The health effects linked to lead exposure are very significant, and so we shall elaborate further on its nephrotoxic impact. It has been established that chronic exposure to lead levels measured in the blood from 70 to 80 μg/dl are a risk factor in the development of CKD of tubulointerstitial origin. The nephrotoxic effect of acute exposure to lead in infant populations has been documented for a long time (Inglis et al., 1978). Currently, levels of exposure have decreased and so have lead plasmatic concentrations. However, a significant number of epidemiological studies have shown that even much lower lead concentrations (10 μg/dl) pose a risk of CKD (Payton et al., 1994; Kim et al., 1996). As is the case with arsenic, exposure to lead has been linked to hypertension and mellitus diabetes, and since both conditions induce renal damage, they are associated with the development of CKD (Ekong et al., 2006). Given the data, we can infer that lead concentrations in the blood in exposed populations may be considered a risk factor for CKD.

According to a study by Castillo et al. (2003), chrome is another highly contaminant heavy metal found in some of the wells sampled in the region. The nephrotoxic effect of acute exposure to chrome has been widely documented; it has even been taken as a model for studying acute renal disease (Arreola Mendoza et al., 2006). In the case of chronic exposure to chrome, renal effects have also been reported, especially renal tubular injury caused by the presence of low molecular weight proteinuria (Wang et al., 1994).

17.3.3 Susceptibility of Infant Populations to the Development of CKD

CKD is characterized by a progressive loss of renal function over three months or more. It has been defined as permanent and progressive damage manifested by a glomerular filtration at less than 60 ml/min per 1.73 m^2 of body surface. Renal damage is characterized by abnormalities and damage indicators, with alterations in the composition of blood or urine identified through renal image studies (National Kidney Foundation, 2002). CKD causes are diverse; they include genetic, socio-economic, racial, and more recently environmental factors. In children, causes are usually distributed amongst hereditary uropathies, chronic glomerulopathies, nephronophthisis, the Alport syndrome, and cystinosis. However, environmental factors in the infant population have not been sufficiently studied. CKD is classified into 5 stages depending on damage, taking the rate of glomerular filtration as an indicator. Average life quality and the patients' diagnostic depend on the stage of the illness at diagnosis and treatment. Treatment for chronic renal insufficiency consists in peritoneal dialysis, haemodialysis, and chirurgical treatment through renal transplants, all of which imply high costs.

Medical attention for CKD is costly and it has been included in the 'Seguro Popular' programme, as Aguascalientes in considered a catastrophic state. This implies a high expenditure for any patient and health system (Shih, 2005). In some social security institutions attention costs for these kinds of patients accounts for up to 17 per cent of the total budget. Prevalence of CKD in the under-18 population has been reported at 14.1 to 54 per million (Deleau, 1994), reaching 74.7 per million if we consider the under-20 population (Ardissino et al., 2003).

Pharmacokinetic processes (absorption, distribution, metabolism, and elimination) differ between distinct population groups; age is one of the most important factors accounting for these differences. The concentration of any endogenous, pharmaceutical, or toxic compound in the organism depends directly on the aforementioned processes. Consequently, age is an important determinant for susceptibility to these effects. Elimination of endogenous and exogenous substances plays a fundamental role in the kidney; it is well known that filtration, secretion, and reabsorption processes are deficient in the early stages of life. This implies that the elimination capacity of toxic compounds among the infant population is lower than that in adults (DeWoskin/Thompson, 2008). Thus, infants are more vulnerable to exposure to chemical compounds and other toxics compared to other age groups. Besides this diminished capacity for elimination, enzymatic biotransformation and detoxification systems have not fully developed at this age, and so xenobiotics remain longer in the body and augment their toxicity. Compared with adults, children eat more and consume more water in relation to their weight. If water is polluted, children are more affected than adults. For example, children drink about two and a half times as much water as adults, and where there is pollution they take in more than twice the pollution that adults do (70 ml/kg versus 28 ml/kg). Nonetheless, as the dose of pollutants infants and adults take is the same, the toxic concentration in the blood will be higher in children merely due to weight and height differences.

Taking into account this higher susceptibility, one of the central questions becomes "Are the standards established by official legislation safe for the infant population?" In this regard, this research team has undertaken various studies in order to seek evidence of early renal damage associated with heavy metal (lead and cadmium) polluted water among the population, even at concentrations below legally established averages. The populations selected for these studies live in rural villages in the municipalities of Aguascalientes, where the wells supplying water to the community present lead and cadmium concentrations slightly below official standards (NOM 127-SSA1-1994). These results coincide with Jarüp's reports (2000), finding early deleterious renal damage, such as tubular proteinuria linked to cadmium at concentrations of around 0.005 mg/l; at these levels, the elimination of cadmium through urine was 1.16 μg Cd/g of creatinine. These results coincide with previous studies that show deleterious effects in renal activity, especially proteinuria, even when urinary elimination of cadmium is at 1.0 μg Cd/g of creatinine (Noonan, 2002).

During the last decades, it has been demonstrated that the kidney is the main target of cadmium as a toxic agent (Jarüp, 2009). In the case of chronic exposure to cadmium through water or diet, renal damage is characterized by proximal tubular dysfunction, having an increase in the urinary excretion of low molecular weight proteins as the earliest clinical sign. Also, recent studies on populations exposed to cadmium suggest that early tubular injury evolve to more serious glomerular damages characterized by a decreased glomerular filtration rate, evaluated by creatinine depuration (Kobayashi et al., 2008). In the case of exposure to either prolonged or higher levels of cadmium, or where individuals present predisposition factors, this may lead to irreversible chronic kidney disease (Hellström et al., 2001; Bandara et al., 2008). Overall, these results make clear that even if cadmium concentrations in water do not surpass the maximum legal limits, they may be an important environmental factor linked to the development of CKD.

Similar effects were observed in populations that consume water from wells with lead concentrations below the NOM official standards (0.025 mg/l; Torres, 2006). Consequently, the effects of heavy metal pollution on water for domestic use may actually represent a more serious and underestimated problem. This could imply that maximum permissible limits for lead and cadmium do not guarantee the health of chronically exposed infant populations.

17.3.4 Prevalence of Chronic Kidney Disease (CKD) Amongst the Infant Population of the State of Aguascalientes

Although there are no clear data on the prevalence of CKD among the infant population at the national level, an incidence of 3.5 new cases per million has been reported at the national level in children under 15 years of age (Gastelbondo/Meza, 2002). Undoubtedly, whatever the parameter of comparison, the prevalence of CKD in the state of Aguascalientes is alarming. Epidemiological studies undertaken in collaboration with the Health Ministry of Aguascalientes, the *Mexican Social Security Institute* (IMSS), and the British Columbia Centre for Disease Control (Vancouver, Canada) reveal that CKD in the state's infant population has reached alarming proportions. There have been 7,000 cases per million children under 15 years of age (Góngora Ortega, 2008), and the municipality of Calvillo alone has 44 per cent of all cases of CKD in the state. Following from this data, it comes as no surprise that the state of Aguascalientes has recently become the leading place for kidney transplants at the national level.

17.4 Conclusions

Demographic and climatic conditions, together with unsustainable anthropogenic activities, put the availability and quality of water at risk. Over the past few years, these factors have had severe impacts. Consequently, one of the hardest and greatest problems of this century is precisely water supply. However, water quality is an aspect that should not be relegated to second place, given its important consequences for human health. This chapter has discussed the regional problem of water quality in the aquifers that supply water to most municipalities of the state of Aguascalientes, where high concentrations of heavy metals, arsenic, and fluorides are present. The human organism is highly susceptible to the effects of these compounds, and most xenobiotics are considered as nephrotoxic agents, even if their action mechanisms are still under discussion. Another crucial factor to bear in mind is that the nephrotoxic potential of these substances increases when pollutants mix, presenting kinetic interactions and modifying their average life and toxicity in human organisms. Also, it is imperative to revise the maximum limits set in the official legislation (NOM), as recent information provides evidence that questions the safety surrounding existing concentration limits of various xenobiotics in water for human consumption.

The problem of pollution in the aquifers is complex, although it may partly answer the question concerning the high prevalence of CKD amongst the infant population of the state of Aguascalientes. Thus, it is indispensable to conduct risk evaluation studies to find out whether a causal relationship exists between pollution in aquifers and the development of this pathology. This would enable Mexican authorities to adopt prevention and remedial measures to limit the impact this has had on the population, minimizing the high costs in economic and life quality terms that affect individuals, families, and society as a whole.

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18 Environmental Study on Cadmium in Groundwater in Yucatan

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18.1 Introduction[1, 2]

The geology of Yucatan is karstic, with many caves and sinkholes, deciduous vegetation, and a slight topographical slope in the landscape. The only water source consists of a fragile system of aquifers which consist of a freshwater layer floating over saline water. This freshwater layer is very susceptible to human disturbances. Since this is the sole water source in the state of Yucatan, it is important to know it and to monitor its quality.

Yucatan's economic activities, such as chicken, pig and cattle farming, agriculture, industry, and trading, are possible contamination sources of groundwater. For groundwater quality for human consumption, levels of trace metals (in this particular case cadmium) are indicators of contamination, because in high concentrations the quality of groundwater can deteriorate and cause serious health problems for humans. Cadmium (Cd) is a heavy metal associated with human activity that is widely used in many industrial processes such as metal plating, batteries, pesticides, fertilizers, and the manufacturing of plastic. It is known that cadmium causes various health problems such as skin, gastrointestinal, kidney, liver, bone, immune system, cardiovascular, and reproductive system conditions.

Studies performed by Pacheco (2004), using cadmium-determining techniques established by Mexican standards, and comparing these data with the allowed limits, demonstrated cadmium occurrence in groundwater, and classified the cadmium levels into two groups: the first with concentrations below 0.02 mg/l, which was the minimum detectable and could or could not meet the required levels established for Cd in the official standard (0.005 mg/l); and the second group, with concentrations of 0.021–0.062 mg/l, which exceeded the allowed levels in 72 per cent of the samples analysed.

These studies led to a protocol for analysis dealing with: a) assurance of quality control of the regulated analytical procedures for determining cadmium, which is a major scientific method with sufficient methodological complexity to ensure the reliability of the results; and b) the development of a sampling protocol, which includes careful planning of the procedures for collecting, handling and transferring samples, as well as for the location and frequency of the sampling, based on the results obtained by this study as a preliminary sampling.

18.2 Groundwater Contamination

Trace metals like cadmium occur in groundwater through volcanic activity, erosion, leaking surface and deep deposits, rocks, mining, metal refining, foundries, and coal and oil combustion. Furthermore, metal works and metal-based products for industrial processes, agriculture and farming, toxic waste disposals, cemeteries, accidental chemical spills, injection wells, and leaching of landfill (Cardenas, 2001; Chi et al., 2006) also contribute to groundwater contamination.

The impact of groundwater contamination depends on the magnitude of the trace element present (single or multiple elements), on the time length of the input, on physical and chemical forms, and on associated chemical substances. These factors determine the concentration of the element in water, and its relative availability, transport, and toxicity. The chemical form is the most important factor, and depends on the pH, solubility, temperature, the nature of other chemical types present, and on other ground-

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2 Keywords: groundwater, karst, cadmium, analytical quality assurance, statistical techniques.

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water factors (Chi et al., 2006; Fifield/Haines, 2000; Price, 2003).

Natural soil profiles actively attenuate many water contaminants, although not all of them. Additionally, the hydrodynamic dispersion associated with groundwater flow usually results in the dilution of persistent and mobile contaminants, especially in the saturated zone of the aquifers. There is more dilution in the extraction wells, due to the fact that they intercept or induce the groundwater flow to different depths and directions, and not all of them are contaminated.

Concern about groundwater contamination is mainly related to the so-called non-confined or phreatic aquifers, especially in those places where the non-saturated zone is thin and the phreatic level is shallow. In general, groundwater supplies derived from deeper and highly confined aquifers are not affected by the soil surface contaminants, except for the most persistent contaminants which tend to have an effect in the very long term (Albert, 1990; Manahan, 1994).

The karstic nature of Yucatan makes groundwater, as the sole supply, very vulnerable to contamination. In most municipal supply systems, the land use of surrounding areas is mainly housing, agriculture, and farming. Consequently, the uncontrolled use of chemicals and inadequate waste disposal are considered potential sources of contamination of groundwater (Ávila, 2006).

18.3 Cadmium Occurrence in Groundwater

Cadmium is a naturally occurring heavy metal that is rare and not abundant. Cadmium enters into the environment either by natural means or through anthropogenic activities such as residual sludge and manure, phosphate and nitrogen fertilizers, plating and galvanizing industries, enamel coating and glass industries, copper, zinc, lead and other metal mining, metal foundries, burning, phosphate feeds for animals, and volcanic activity and rocks (Roberts, 1996). Of the human-generated cadmium, less than 10 per cent is recycled by industries. This means that most cadmium is accumulated in the environment (Wright/Welbourn, 2002).

Soil characteristics have a direct influence on the solubility and consequently on the bio-availability of Cd. Among these characteristics, soil pH is considered the most important factor. At a lower pH (2–4) Cd becomes more soluble, and vice versa (Alloway, 1990). Cadmium is soluble in water, but not degradable; it rather changes its form, enters into plants and aquatic animals, and accumulates. Some of the major chemical types that are found in natural water are CdCl+, $CdCl_2$, Cd2+ and $CdCl_3$- (Fifield/Haines, 2000; La Fuente/ Mouteira, 1999; Manahan, 1994).

Cadmium is a metal that has only come into use very recently. Before World War II, there was practically no demand for it, and it was seen as an impurity in zinc and lead which was discarded, creating large contamination areas around these metal industries. In modern times, Cd contamination is still associated with these industries, plus waste burning, coal combustion, the steel industry, concrete production, and artificial phosphate fertilizers (Albert, 1990; Derache, 1990; EPA, 2005, 2005a; Underwood, 1973).

The maximum permitted cadmium levels in groundwater for public supply, according to the Mexican standard NOM-127-SSA1-1994, is 0.005 mg/l. This level refers to total concentration in water, which includes cadmium as suspended material and in solution (EPA, 2005a).

According to the *World Health Organization* (WHO), the amount of cadmium in drinking water should not exceed 0.005 mg/l (5 µg/l), and the weekly mean of Cd consumption in a normal diet should be between the range from 0.0028 to 0.0042 mg per kg of body weight (2.8 to 4.2 µg/kg body weight) (WHO, 1995, 2000; Wright/Welbourn, 2002).

Recent research has proved that exposure to small concentrations of cadmium can alter the bone structure, increasing the risk of fractures. This is due to the fact that cadmium can interfere with the calcium metabolism, vitamin D, and bone collagen, and in the long run this produces bone conditions such as osteomalacia and osteoporosis (Staessen et al., 1999).

Cadmium supplied by phosphate fertilization can be absorbed by the crops and reach people who consume them. Vegetables look healthy and vigorous even though they contain more cadmium than normal. In Japan, 'Itai-Itai' disease has been observed in humans, due to the long-term intake of cadmium-contaminated rice (Carrasco, 1994; Staessen et al., 1999; CONAMA, 2001).

An increase in Ca^{2+}, Zn^{2+} and Fe^{3+} intake can diminish cadmium, copper, or mercury absorption. But excessive cadmium in the diet can produce symptoms associated with Ca^{2+} deficiency in humans. In the case of pancreatic carboxypeptidase (zinc dependence) there is a decline in its activity and specificity if cadmium, lead, copper, or nickel is present, by the binding of zinc from the active site (Tapia, 1994). Cadmium can replace calcium in bones, with dire consequences, as was verified in Japan during the 1950s for farmers who lived in contaminated lands near a zinc-cadmium mine (Villanueva, 2001).

There is background evidence that links cadmium to testicular tumours and prostate cancer in workers who have been exposed to it (Tapia, 1994). It has been proved that the kidney is the critical organ for cadmium (WHO, 1992; UNEP, 1992). Chronic exposure to cadmium can produce nephrotoxicity (Tang, 2000). Another hazardous situation, particularly for children, is the presence of Cd and Pb in eggs from chickens fed with inorganic materials (Dey/Dwivedi, 2000). The body absorbs approximately 5 per cent of the Cd from food and water, and 10 per cent from cigarette smoke. A pack of 20 cigarettes contains an average of 20-25 g of cadmium. A non-smoker in a non-contaminated area would absorb nearly 0.5–1.3 g of Cd a day from food and water (Roberts, 1996).

The WHO established in 1972 that the *Maximum Allowable Daily Level* (MADL) of Cd should not exceed 1 [g kg-1] of body weight (that means 70 [g day-1] for an average person). Dietary intake of cadmium was estimated at 15–30 [g day-1] for North Americans, and 20–40 [g day-1] for Europeans (OECD, 1994). Since food is the major source of Cd intake, hazard reduction strategies could have important consequences for agriculture (Roberts, 1996).

There are three described and established techniques for determining cadmium in order to certify drinking water quality: *graphite furnace atomic absorption spectrometry* (GFAAS), direct flame absorption spectrometry, and the dithizone colorimetric method. The first-mentioned is the most precise. The GFAAS technique is also the most sensitive, because it requires a background correction to be performed in order to minimize erroneously high values. Graphite tubes are used in order to minimize chemical interference, and argon to prevent metal oxidation. As a result, this technique provides very precise readings (APHA/AWWA/WEF, 1992).

Several studies were conducted in Yucatan on water contamination by cadmium and the possible degree of contamination or its impact on the aquifer. Trafford et al. (1994) conducted a study in the city of Merida in 1991 to determine the occurrence of metals in groundwater, finding Cd, in concentrations below detection, with an average level of 0.03 mg/l. Sauri and Comas (1995) evaluated the aquifer between 1990 and 1991, and compared results with those obtained in the same area from 1981 to 1982. Cadmium could not be detected in 51.5 per cent of the shallow wells. The highest level of 17.6 µg/l was found in well number 8 in July 1990, the only one that exceeded the recommended concentration established by the WHO (5 µg/l). This value triggered a concern that the sampling point had been subject to an unusual event during that month.

None of the deep wells exceeded the guideline cadmium levels set up by the WHO, and cadmium was detected only in 66 per cent of them, possibly because the metal was distributed because of the aquifer's characteristics. The exception was observed during the month of July, where the average values of cadmium for wells of 18 m or deeper exceeded those of shallow wells, and in October 1990, when the maximum concentration was detected. This could be attributed to the end of the rainy season, when heavy downpours could have favoured the infiltration of Cd into the aquifer.

Pacheco (2004), in a study to delineate the boundaries of a hydrogeological reserve which includes the main drinking-water supply wells of Merida, Yucatan, registered an average cadmium concentration of 0.02169 mg/l in 39 sampled wells during the rainy season, with a standard deviation of 0.03167, and maximum and minimum values of 0.2 mg/l and 0.007 mg/l, respectively. During the dry season, 44 wells were sampled, giving average Cd values of 0.01832 mg/l, with an SD (standard deviation) of 0.01832 mg/l, and maximum and minimum values of 0.03 mg/l and 0.012 mg/l, respectively.

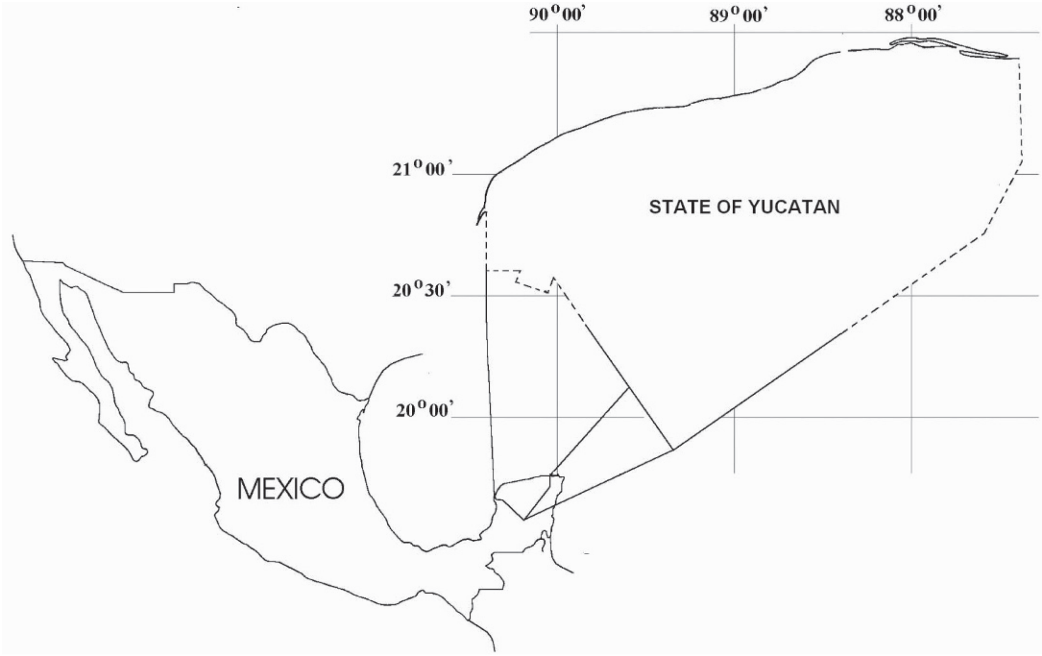
The studies showed the presence of cadmium in groundwater at concentrations that sometimes exceeded the permitted levels, therefore further studies are required.

18.4 Area of the Study

The state of Yucatan is located in the south-east of Mexico, in the north of the Yucatan peninsula (figure 18.1). The climate of the region is hot sub-humid with summer rains, according to Köppen's system modified by Garcia (1981). There are two well-defined seasons: the dry season which extends from November to April, and the rainy season which extends from May to October. The mean temperature of the region is 26ºC (16.2-35.6°), with an annual rainfall of 500 mm in the north-west, and 900–1,100 mm in the south-east (INEGI, 2002).

There are no surface water streams in Yucatan; as a result, a significant amount of water evaporates, and the rest filters into the ground through cracks and

Figure 18.1: Study area. **Source:** The authors.



crevices found in the limestone at different depths. The Yucatan's aquifer is a free type, although there is a coastal band of 5 to 30 km wide, with aquitard characteristics, and clayey soils in the southern region. Groundwater is saturated with calcite, but as it gets closer to the coastline, it combines with salt water which results in an unsaturated mixture that dissolves carbonates and widens the cracks and crevices (CONAGUA, 2004). It is one single aquifer with a marked heterogeneity in its hydraulic characteristics; therefore, there is only one water table, with stratified variations in the water quality. Fresh and tolerable water is found in most parts of the state, and salt water is located in the south-east and adjacent to the coast (INEGI, 2002).

Yucatan's aquifer is an open hydrological basin in natural conditions. A horizontal zoning in the water quality can be observed in the central area. The upper part contains fresh water with a near 40 m depth which rests on a mixture zone or saline interface, and at an approximate depth of 60 m there is salt water (Villasuso, 1980). The depth of the static levels varies according to the distance from the coast; between the coast and Merida the depth is 1–5 m; between Merida and the Puuc zone the depth is 10–30 m; and beyond the latter, 60–100 m (CONAGUA, 2004).

The flow direction is determined by the complex underground morphology which features crevices, galleries of different shapes and diameters, interspaces, levels of stratification, etc. However, it can be stated that the water flow is radial, beginning from the south of the state towards the coastline with preferential SE-NW, S-N and SW-NE flow directions, in a highly complex cavernous surrounding (INEGI, 2002).

18.5 Objectives

This chapter has six objectives:

a.) to design an environmental sampling protocol that enables the determination of cadmium concentrations in the groundwater of Yucatan;
b.) to establish quality assurance for the chemical analyses for cadmium determination in groundwater samples with an acceptable degree of confidence regarding precision and repeatability;
c.) to construct a geo-referenced map of cadmium concentrations in the groundwater of Yucatan, based on the use of geostatistical methods;
d.) to compare the cadmium concentrations with the established levels in Mexican standard NOM-127-SSA-1994, in order to determine its potential impact on public health;
e.) to compare these levels with previous data (time variability); and
f.) to assess possible risks to people's health by characterizing non-carcinogenic hazards by oral intake of cadmium in groundwater.

18.6 Methodology

18.6.1 Environmental Sampling Protocol Design

The following aspects were considered in designing the sampling protocol:

a.) *Purpose of the sampling*: Everyone involved was instructed about the objective of the study so that they could acknowledge the importance of obtaining reliable, good quality data.
b.) *Target chemical substances*: The key aspects relating to the chemical substances to be studied were defined as chemical properties, environmental importance, methods of analysis, sampling volume, sampling technique, types of preservatives, and handling procedures for the sample.
c.) *Location of the sampling sites*: The sites were chosen based on the results from the project "Groundwater quality in drinking water extraction wells and assessment of infrastructure of water supply systems and facilities of municipalities in the state of Yucatan", code: YUC-2002-C01-8721 (Pacheco 2004a), and this was used to calculate the number of samples.
d.) *Selecting the sample points*: The most important consideration at this stage was *the minimal disturbance of the sample*, because certain micro-environments can be created or altered by the sampling instruments.
e.) *Collecting the sample*: Special attention was given to the sampling instruments and the quality of the materials of which they were constructed; the routes that samples followed were revised to minimize systematic error sources.
f.) *Sample handling, preservation, storage and transportation*: The corresponding manuals were revised for each of the aforementioned procedures. However, care was taken to perform as few manipulations as possible.

18.6.2 Quality Control Assurance of the Analyses

Cadmium determination was performed at the Analytical Chemistry Laboratory of the Chemistry School, Autonomous University of Yucatan, using *graphite furnace atomic absorption spectrometry* (GFAAS), as described in the Standard Methods. This is the most sensitive method because it requires performing a background correction to minimize erroneously high values. Additionally, the graphite tubes minimize chemical interference and argon gas is used to prevent the oxidization of metals. As a result, this technique provides very precise readings (APHA/AWWA/WEF, 1992).

18.6.3 Elaboration of a Geo-referenced Map

Following the sampling protocols and chemical analyses, the results were analysed by means of geostatistical procedures to determine the model that best suited the data, and to obtain the value of the coefficient of determination for the selected model (GS+ software). The chosen model was used to obtain a cadmium isoconcentration map which allowed areas with higher metal concentrations to be recognized (SURFER v8 software).

18.7 Results and Discussion

18.7.1 Environmental Sampling Protocol Design

The environmental sampling protocol allowed the environmental situation related to cadmium concentration in groundwater to be diagnosed. In this sense, it was very important to ensure that samples were representative by selecting the sampling points adequately, describing the procedures and activities to be performed before, during, and after the sampling, as well as providing the criteria to interpret, process, and report the results.

18.7.2 Control and Assurance of Analytical Quality

The equipment and analytical technique used allowed quantification limits of 0–30 μg/l (0.030 mg/l) to be obtained. The calibration curve (figure 18.2) was constructed using a cadmium standard NIST traceable AccuTrace with a correlation coefficient of 0.9885. This coefficient guaranteed the quality control of the readings.

18.7.3 Cadmium Concentrations

Cadmium concentrations of groundwater samples from municipal water supply wells were detected in 100 per cent of the samples, and the values ranged between 1 and 15 μg/l (table 18.1), within the detection range of the technique used.

Figure 18.2: Calibration curve for cadmium determination in groundwater. **Source:** Authors' research data.

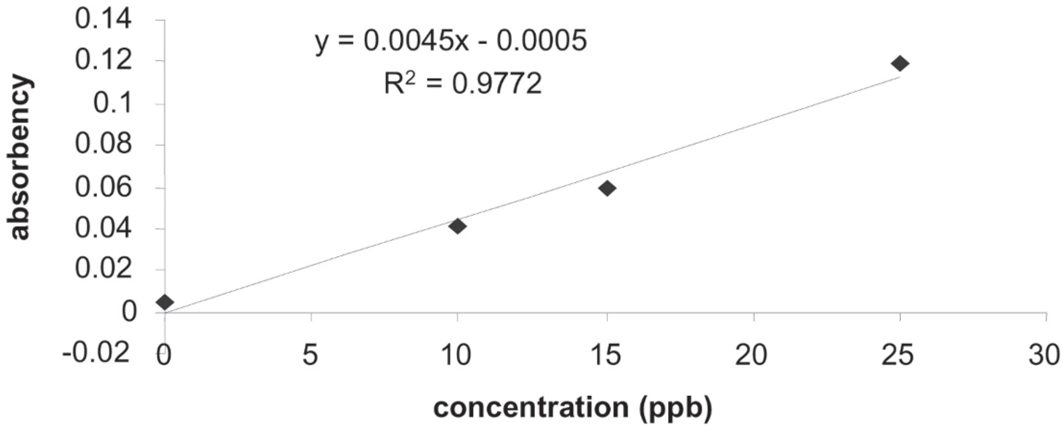


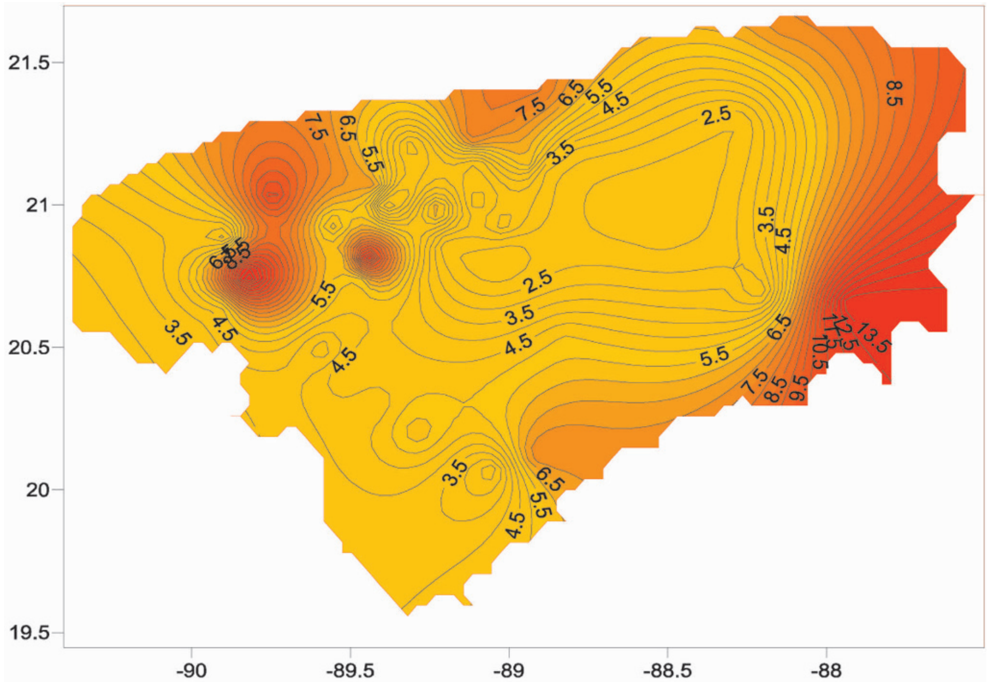
Table 18.1: Cadmium concentrations in ppb (parts per billion). **Source:** Authors' research results.

	Repetitions				
	1	2	3	4	
Location	**Conc. (ppb)**	**Conc. (ppb)**	**Conc. (ppb)**	**Mean**	**SD.**
Ucu	12.22	6.47	11.76	10.15	3.20
Celestun	3.33	2.35	2.94	2.87	0.49
Kopama	2.44	4.16	5.88	4.16	1.72
Ticul	3.11	8.24	7.65	6.33	2.81
Oxkutzcab	3.11	2.94	6.47	4.17	1.99
Peto	1.11	13.53	14.71	9.78	7.53
Sacalum	2.22	4.12	2.94	3.09	0.96
Kantunil	1.11	1.77	1.76	1.55	0.38
Homun	2.00	5.29	5.88	4.39	2.09
Yaxkaba	6.00	2.35	2.94	3.76	1.96
Acanceh	4.46	4.71	4.12	4.43	0.30
Timucuy	5.33	10.59	2.94	6.29	3.91
Cacalchen	6.45	5.88	7.65	6.66	0.90
Tekanto	1.56	3.53	2.35	2.48	0.99
Izamal	3.11	5.29	3.53	3.98	1.16
Chemax	4.71	4.71	4.71	4.71	0.00
Tixpehual	3.33	2.84	2.35	2.84	0.49
Muxupip	1.56	3.53	2.35	2.48	0.99
Yaxkukul	1.78	9.42	5.6	5.60	3.82
Uayma	3.56	3.53	1.76	2.95	1.03
Conkal	3.24	3.53	2.94	3.24	0.30
Yobain	4.42	4.12	4.71	4.42	0.30
Dzoncahuich	3.56	2.94	1.76	2.75	0.91
Temax	2.36	1.77	2.94	2.36	0.59
Sucila	1.00	1.77	2.94	1.90	0.98
Rio Lagartos	8.2	5.13	7.95	7.09	1.70
Chochola	18.72	13.08	12.05	14.62	3.59
Chapab	4.62	5.13	5.13	4.96	0.29
Kanasin	3.08	3.59	4.1	3.59	0.51
Baca	4.36	4.62	6.15	5.04	0.97
Buczotz	3.08	2.82	2.31	2.74	0.39
Dzitas	3.85	2.05	1.54	2.48	1.21
Tecoh	5.64	4.10	5.9	5.21	0.97
Sudzal	2.31	1.80	2.31	2.14	0.29
Valladolid	2.31	2.31	2.82	2.48	0.29
Samahil	1.54	1.28	1.28	1.37	0.15
Tekax	7.44	6.15	5.9	6.50	0.83
Temozon	2.56	3.08	2.31	2.65	0.39
Suma	2.56	3.08	3.59	3.08	0.52
Panaba	2.56	1.80	1.54	1.97	0.53
Dzilam Bravo	8.46	7.44	7.18	7.69	0.68
Tixkokob	1.8	0.77	1.54	1.37	0.54
Hoctun	1.54	2.05	2.05	1.88	0.29
Cansahcab	1.54	2.31	2.05	1.97	0.39
Tixcacalcupul	4.62	4.87	4.36	4.62	0.26

18.7.4 Analysis of Variance

The use of statistical methods for the results obtained from analytical techniques plays a critical role in verifying the quality control assurance of the chemical analyses. Therefore, a normal probability chart was constructed with the values from the three measurements for each of the samples, in order to verify the suitability of parametric or non-parametric statistical

Figure 18.3: Cadmium isoconcentration map (μg/l). **Source:** Authors' research results.



methods for the correct interpretation of the results. Since the values obtained did not follow a normal distribution, the Kruskal-Wallis non-parametric technique was applied to verify whether there were significant differences between the values obtained from the three repetitions for each of the samples analysed.

Kruskal-Wallis is a non-parametric test that uses data ranges of three or more independent populations. It is used to test the null hypothesis (H_0) which states that independent samples arise from populations with a similar distribution, whereas the alternative hypothesis (H_1) states that population distributions are different in some way.

The results showed the statistical test H=0.9547 (table 18.2) did not fall in the 5.991 region identified as corresponding to 2 degrees of freedom at a 5 per cent significance level. Therefore, the null hypothesis of identical populations was not discarded. A similar reasoning was made for the p value. It was therefore concluded that there was not enough evidence to sustain populations from the readings obtained, the three repetitions of each sample showing statistically significant differences. In analytical chemistry terms, the latter meant that results from the repetitions were exact with a confidence level of 95 per cent.

Table 18.2: Kruskal-Wallis analyses results. **Source:** Authors' research results.

Kruskal-Wallis test factors	H (2, N=144) = 0.9547358
P value	0.6204

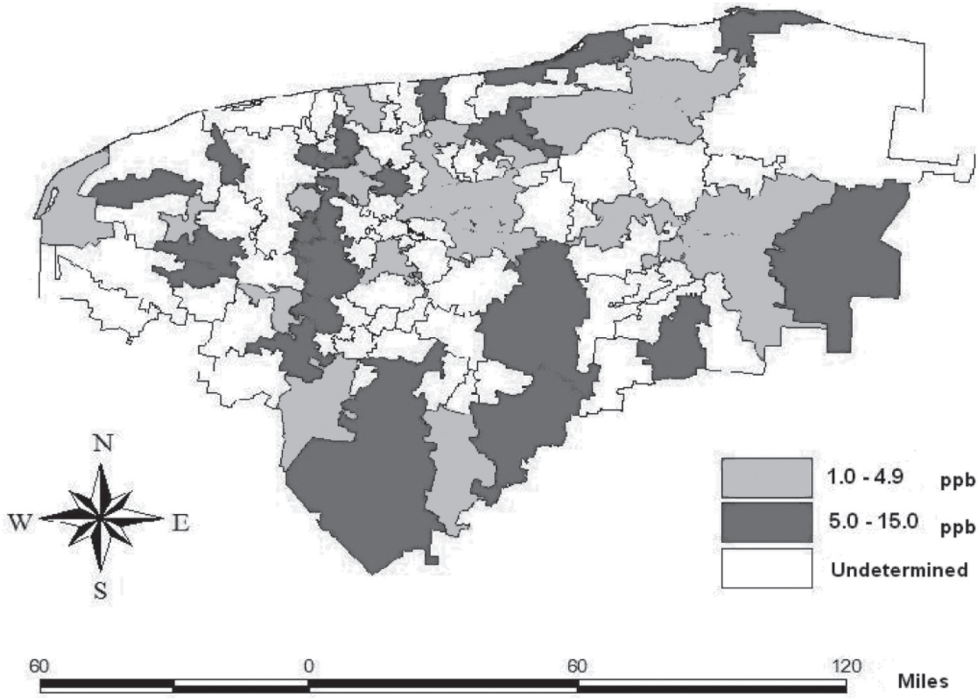
18.7.5 Isoconcentration Map (Geo-referenced)

The values obtained for the mean were used to obtain the experimental variogram and the adjustment model (theoretical variogram). Once the model with the best fit was obtained, a cadmium distribution map showing isoconcentrations was constructed (figure 18.3).

The isoconcentration map showed the highest concentrations in the north-western, eastern, and coastal zones. It is possible that the levels found were due to poor waste management from pig and poultry farms, and the use of phosphate fertilizers with high cadmium levels, as well as to open-air garbage dumps where debris containing cadmium could be found, hence infiltrating the groundwater.

Given the fact that groundwater is the main water source in Yucatan, it is necessary to use geospatial tools and *geographical information systems* (GIS) to take advantage of databases with geographical features in a systematic and integrated way in order to assist in decision-making for the conservation of this resource. Therefore, a map was constructed showing

Figure 18.4: Cadmium concentrations in groundwater from the municipalities of Yucatan. **Source:** Authors' research results.



25 supply wells corresponding to those municipalities where the cadmium levels found were equal to or above 5µg/l, the maximum level allowed by Mexican standard NOM-127-SSA1 1994.

Some of these municipalities are very close to each other (figure 18.4), which suggests there is a common activity or source of contamination, which could be hydrocarbons, corroded galvanized pipes, phosphate fertilizers, or open-air waste yards.

18.7.6 Cadmium Concentrations and Maximum Permitted Levels Established by Mexican Standard NOM-127-SSA-1 (1994)

The highest cadmium concentrations found in those analysed water samples which exceeded the level of the Mexican standard were observed in 29 per cent of the wells, with values ranging between 6 and 15 µg/l. These samples corresponded to 14 municipalities: Acanceh, Cacalchen, Chemax, Chochola, Conkal, Dzilam Bravo, Peto, Rio Lagartos, Tekax, Temax, Timucuy, Ucu, Yaxkukul, and Yobain (figure 18.5).

18.7.7 Temporal Variations of Cadmium Concentrations in Groundwater

Cadmium concentrations detected in 48 of the groundwater samples in the present work (2007) were compared to the concentrations reported for the same sampling sites in 2003 (figure 18.6). It is worth mentioning that in 2003 the sampling comprised the 106 municipalities of the state, where the maximum permitted level was exceeded in 92 per cent of the samples with values ranging between 21 and 45 µg/l, with a generalized trend towards increased concentrations throughout the state (Chi et al., 2006). There are three possible sources that could account for these increased cadmium levels: a) the existence and poor management of pig and poultry farms, b) the presence of open-air garbage dumps, and c) the overuse of agricultural chemical products, mainly fertilizers. The latter are extensively used in the southern region of the state, where an increase in vegetable crop production has been observed in recent years, and there is a continuous demand for fertilizers.

However, the increased cadmium levels could have been favoured by the passing of Hurricane Isidore, which caused a huge reload of the aquifer, and for this reason the results obtained in the 2007 period

Figure 18.5: Municipalities of Yucatan with cadmium concentrations above permissible levels. **Source**: Authors' research results.

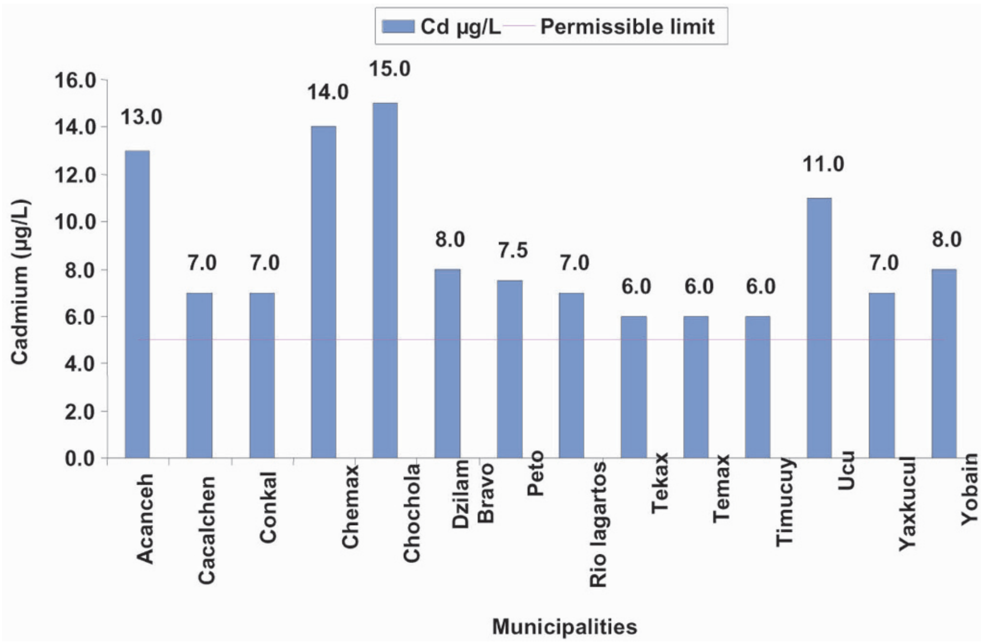
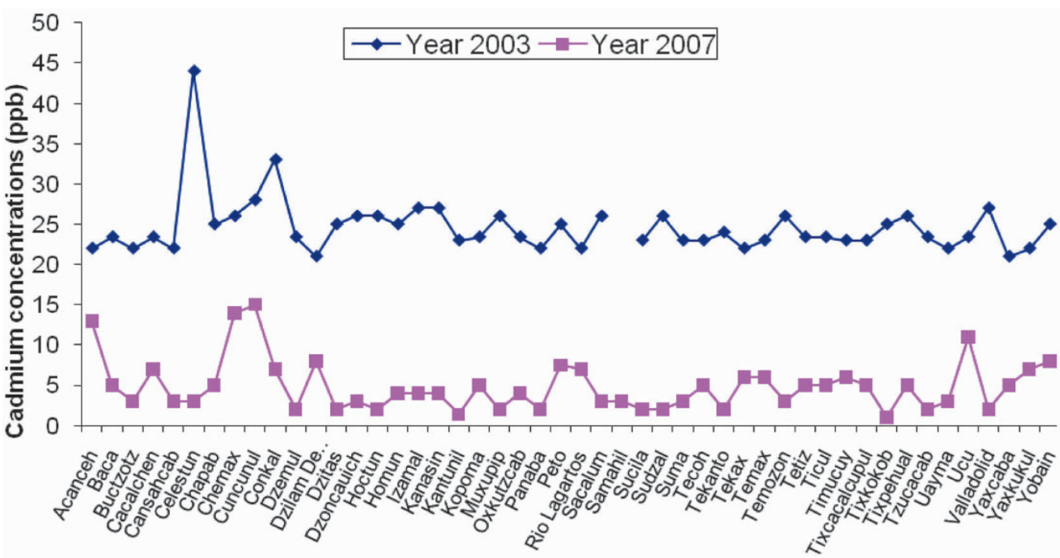


Figure 18.6: Temporal variations of cadmium concentrations in groundwater. **Source:** Authors' research results.



could represent a better reflection of the anthropogenic activities previously mentioned.

18.7.8 Hazard Characterization

Non-carcinogenic hazard by oral intake was calculated in two ways: first, a hazard index was produced based on the Cd concentration classification obtained in 2007 (table 18.3).

Table 18.3: Municipality classification according to Cd levels. **Source:** Authors' research results.

Municipalities	Cd levels in relation to permissible limits
Group 1	1-4.9 µg/l Cd
Group 2	5-15 µg/l Cd

The reference daily dose values (OECD, 1994) are shown in table 18.4.

Table 18.4: Reference daily dose for cadmium. **Source:** OECD (1994).

Substance	Cadmium
Reference dose (RfD (mg/kg) * day)	0.0005

18.7.8.1 Hazard Quotient (HQ) Obtained for Cadmium

The hazard quotient formula for a 60 kg person consuming 3 litres of water was calculated as:

$$HQ = \frac{DDP}{RfD} = \frac{[Cd_{Average}]\ (mg/l) \times (3\ l/day)}{(0{,}0005\ mg/kg\ {}^{*}day)\ (60\ kg)}$$

Using the average value for each concentration range (mg/l) and EPA's established reference dose, the estimated daily dose and the hazard quotient were obtained (table 18.5).

Table 18.5: Hazard quotient for cadmium. **Source:** Authors' research results.

Municipalities	Average Cd (mg/l)	DDP (mg/day)	RfD (mg/day)	HQ Cd (mg/day)
Group 1	0.002	0.007	0,03	0.26
Group 2	0.007	0.0219	0,03	0.73

Municipalities with cadmium levels ranging from 1 to 4.9 µg/l presented a HQ of 0.26, indicating a low hazard index. However, municipalities with levels between 5 and 15 µg/l showed a HQ of 0.73, indicating a high risk (of possible health hazards among the population), since the hazard index is considered significant as the value gets closer to 1.

18.8 Conclusions

The design of an environmental sampling protocol allowed the efficient assessment, in terms of budgetary and human resources, of cadmium concentrations in the groundwater of Yucatan. The use of adequate statistical techniques allowed the establishment of quality control assurance for the cadmium-determining analyses in groundwater samples with an acceptable degree of confidence regarding precision and repeatability.

A geo-referenced map for cadmium concentrations in the groundwater of Yucatan was made using geostatistical techniques, which could constitute a basis for further studies and decision-taking regarding groundwater management.

There is a potential and significant hazard to public health caused by the presence of cadmium in groundwater, and this will increase unless proper preventive measures are taken to avoid further deterioration. It is thus necessary to assess potential health hazards by implementing epidemiological studies.

The absence of natural cadmium sources in the region means that most of the cadmium found in groundwater is the product of anthropogenic activities. The presence of cadmium is favoured by the karstic nature of Yucatan's geology, which provides direct routes for water contamination by cadmium.

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19 Fish and Macroinvertebrates as Freshwater Ecosystem Bioindicators in Mexico: Current State and Perspectives

Catherine Mathuriau, Norman Mercado Silva, John Lyons and Luis Manuel Martínez Rivera

19.1 Introduction

In Mexico 78 per cent of water is used for agriculture, 12 per cent for household use and 10 per cent for industry. Once water is used in agricultural settings, wastewater containing agrochemicals and other chemicals is generated and released to rivers. In addition, 14 km^{3}/year[1] is generated from industry (43.8 per cent) and from water use in municipalities (56.2 per cent), which is also released into rivers and lakes throughout the country (CONAGUA, 2008).

Based on the existing infrastructure, 38 per cent of municipal wastewater is treated. However, many municipal water treatment plants do not operate at optimal capacity, and so it is estimated that 62 per cent of wastewater is released untreated to streams and rivers in Mexico (CONAGUA, 2008). Wastewater releases, inadequate agricultural practices, the introduction of non-native species, resource over-exploitation, and stream canalization, among other causes, have modified ecosystem structure and function. These changes have in turn affected social and economic development (Folke et al., 2002).

Since 1974 Mexico's national water commission (CONAGUA) has systematically monitored water quality using a physico-chemical approach. In 2003, *biochemical oxygen demand* (BOD_5), *chemical oxygen demand* (COD), and *total suspended solids* (TSS) are used by CONAGUA to assess water quality. While these parameters are useful for determining the amount of organic matter present in the water, they do not reflect the biological integrity of the ecosystem. The use of only physico-chemical indicators to assess the quality and health of aquatic ecosystems limits our evaluation of the many other effects that humans may be having on these ecosystems.

Biomonitoring techniques were developed to attempt a more integrative evaluation of human alterations to freshwater ecosystems. Techniques that use biological communities to evaluate water quality have been demonstrably successful in evaluating degradation of quality (Cairns/Pratt, 1993). Organisms can integrate physical, chemical and biological conditions of water over varied spatial and temporal scales and these techniques can be used to measure habitat degradation (Prat et al., 1996).

Fish and macroinvertebrates have been widely used as bioindicators (Rosenberg/Resh 1993; Frenzel et al., 1996). These groups have been approved for use in environmental quality protocols in the U.S. (U.S. Clean Water Act), Canada (Canadian Environmental Protection Act) and the European Union (Water framework directive; Neimi/MacDonald, 2004).

The development of the Saprobic System in Germany in the early 20th century is considered to have been the first index using bioindicators for aquatic ecosystems (Kolkwitz/Marson 1908, 1909; in: Cairn/ Pratt, 1993). During the 1960s other European scientists developed new biomonitoring techniques in several countries. In the United Kingdom: the *Trent Biotic Index* (TBI; Woodiwiss, 1964), Chandler's Score (Chandler, 1970), and the *Biological Monitoring Working Party* (BMWP; Armitage et al., 1983); in France: the *General Quality Biologic Index* (IBQG; Tuffery/Verneaux, 1968); and in Belgium: the *Belgian Biotic Index* (IBB; DePauw/Vanhooren, 1983). Since 1955, *Beck´s Biotic Index* (BBI; Beck, 1955, in: Washington, 1984) has been developed and used in the United States. Later on, more indices were created: the *Biotic Condition Index* (BCI; Winget/Mangun, 1979); the *Sequential Comparison Index* (SCI, Cairns/Dickson 1971); the *Family Biotic Index* (FBI; Hilsenhoff, 1988); *Multiparametric Indices* (Plafkin et al., 1989; Barbour et al., 1999); and the *Indices of Biotic Integrity* (IBI; Karr 1981). In Latin America, aquatic ecosystem biomonitoring began in the Antioquia region of Colombia in the 1970s (Roldán et al., 1973; Pérez/Roldán, 1978). Other countries in the re-

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gion began developing these techniques in the 1990s: in Chile (Arenas, 1995; Habit et al., 1998), in Venezuela (Lugo/Fernández, 1994; Rodriguez Olarte/Taphorn, 1995; Rivera/Marrero, 1995), in Argentina (Domínguez/Fernández, 1998), and in Brazil (Barbosa, 1994; Navas Pereira/Henrique, 1995; Kuhlmann et al., 1998). In Mexico, the development of biomonitoring techniques began in the 1990s. In the following chapter, we review Mexican studies that have used fish and macroinvertebrates as bioindicators and discuss the future of these tools for the conservation of freshwater ecosystems.

19.2 Objectives

To review Mexican studies that have used fish and macroinvertebrates as bioindicators and discuss the future of these tools in the conservation of freshwater ecosystems.

19.3 Materials and Methods

We reviewed existing literature addressing the development and use of biomonitoring tools in Mexican freshwater ecosystems (lakes, ponds, marshes, reservoirs, streams, and rivers). We used the following databases: *Red de Revistas Científicas de América Latina y El Caribe, España y Portugal* (REDALYC), *Biological Sciences*, *Aquatic Sciences and Fisheries Abstracts* (ASFA) and the *Scopus* search engine. Keywords used to locate relevant literature were: Mexico, bioindicator*, macroinvertebrate*, fish*, aquatic insect*, hydrobiology, and water pollution.

As well as this, we reviewed Mexican journals with an environmental focus, journals from several federal and state universities, research centres and other public institutions dealing with water issues, and abstracts and proceedings from several organizations. Finally, we used online search engines such as Google and Google Scholar to complete our search. We did not include theses, given the difficulty of accessing the documents.

19.3.1 Results

We found 23 documents addressing fish and macroinvertebrates as biological indicators of water and environmental quality. Six of these focus on the use of fish as indicators and 17 focus on macroinvertebrates. Thirty per cent of the investigations were published in international journals, 26 per cent in symposia proceedings, 17 per cent in national journals, 17 per cent in internal documents, and 9 per cent in book chapters.

19.4 Fish as Freshwater Ecosystem Biomonitoring Tools

For the last 15 years fish have been the most widely used group in the development of freshwater biomonitoring tools in Mexico. They have several advantages over other biological groups (Frenzel et al., 1996): a) there is information on life histories for a large number of species; b) a community can be represented by species occupying several trophic levels and feeding guilds; c) their relative high position in trophic food webs, compared to some macroinvertebrates and diatoms, offers an integral perspective of the ecosystem; d) they are relatively easy to identify; and e) effects of toxicity (i.e., reduced growth, decreased reproductive success) can be evaluated via fish communities.

Fish community structure is determined by habitat conditions and resource availability. Normally, a community established in a certain habitat is composed of organisms adapted to all habitat characteristics and can reproduce using available resources. If a habitat contains all elements and processes required by a certain species, the species has the capacity to occupy an ecological niche (the n-dimensional hypervolume of ecological factors related to the ability of a species to exist and reproduce) within this habitat. It is this capacity that is used in the development of biomonitoring tools.

The use of fish as biomonitoring tools has focused on the development of *indices of biotic integrity* (IBI). IBIs use information on the composition, structure and ecological function of biological communities to evaluate environmental quality. In Mexico there are currently four fish-based IBIs: Lyons et al. (1995, 2000), and Contreras-Balderas et al. (2000, 2005). Some details on each of these indices are discussed in the following paragraphs.

In general, IBIs include information on five different community characteristics: 1) the species richness and the composition of the community; 2) the presence and abundance of indicator species; 3) the trophic and 4) the reproductive function of species in the community; and 5) the condition and abundance of individuals in the community. Once summarized via a series of metrics and scoring criteria, this information is helpful in determining habitat environmental quality. IBIs used in Mexico have included 39 metrics reflecting different attributes of the community (Mercado Silva et al., 2006).

The IBI developed by Lyons et al. (1995) is valid for some streams and rivers in central- western Mexico. Some modifications have been suggested to the original index so that its use can be expanded to other basins in central and eastern Mexico (Mercado Silva et al., 2006). Some of these modifications are significant and reflect the differences in community composition and structure that exist between numerous basins in the country. There are several ongoing investigations that are adopting the basic structure of this IBI and using it to develop indices to be used in the Duero River basin and several springs in Michoacán (Medina Nava, 2003). Since 1996, this IBI (Lyons et al., 1995) has been successfully used in the Sierra Mantlán Biosphere Reserve (Jalisco/Colima) to identify specific sites requiring conservation, protection or restoration activities, and to identify anthropogenic effects occurring in the system. Based on this IBI and independent water quality assessments, local municipalities and education institutions have developed important conservation plans for resource conservation in the Ayuquila River (Patrón et al., 2005).

As part of a bi-national effort for conservation, Contreras Balderas et al. (2000) developed a fish-based IBI to help in the analysis of environmental conditions and historical changes occurring in the Rio Bravo (Rio Grande). Water extraction, groundwater over-exploitation and habitat alteration in the middle and lower Rio Bravo have had important effects on the fish communities of these rivers. This basin is today considered one of the most degraded basins in the country (Contreras Balderas et al., 2008).

From a similar historical perspective, Contreras Balderas et al. (2005) developed an IBI for the lower Rio Nazas (Durango and Coahuila). This river, threatened by pollution and water extraction, is the home to several endangered or threatened species. As a result of the development of the IBI, the authors were able to suggest several management strategies to avoid further deterioration of the basin. Both of these IBIs make use of historical data on fish distribution and abundance to explain changes that have occurred through time, and have been able to establish a baseline condition that reflects the structure and composition of the fish community prior to being degraded by anthropogenic activities in the region.

Severe degradation of lakes in central Mexico, and the uniqueness of their fish community, prompted the creation of a lake IBI (Lyons et al., 2000). This IBI incorporates metrics that help to assess the effect that commercial and subsistence fisheries are having on fish communities and ecosystem health. Metrics based on the maximum size of fish can help the analysis of how a species is being affected by fisheries.

In all of the above cases, IBIs have been used to follow and evaluate conservation measures that have been implemented and to determine their effectiveness, to identify sites that need to be prioritized, to measure ecosystem and community degradation, and to identify factors affecting freshwater communities undetectable by chemical or physical environmental evaluations (i.e., effects of invasive species), among other factors.

The use and development of IBIs continues to expand in Mexico (figure 19.1). Efforts to develop IBIs in the basins of southern and eastern Mexico have begun. The Hondo River (Quintana Roo) and the Grijalva-Usumacinta Basin (Chiapas-Tabasco) have very complex fish communities and are threatened by numerous anthropogenic activities. IBI development in these areas will help in conservation efforts in one of the areas of highest biological diversity in the country. Similarly, IBI development has begun in the Huasteca region of the state of Hidalgo (Panuco River Basin). Numerous streams and rivers in this region have segments that have not yet been affected by anthropogenic activities.

19.5 Macroinvertebrates as Indicators of Environmental Quality in Freshwater Ecosystems

Benthic macroinvertebrates are larval and adult stages of insects, flatworms, annelids, crustaceans, and molluscs. They are generally larger than 0.5mm and live close to the bottom of streams and rivers among the sediment and roots and branches of aquatic vegetation. They have an important role in the ecological processes of aquatic ecosystems: they control primary productivity (Huryn, 1998), decompose leaf litter from riparian areas (Webster/Benfield, 1986), and are a source of food for fish (Power, 1990), birds (Gray, 1993), and bats (Sullivan et al., 1993). Since the beginning of the 20th century macroinvertebrates have been used as environmental quality indicators in aquatic ecosystems and in basin-wide management strategies. Macroinvertebrates are relatively large-sized. They have relatively long life cycles, which allow them to integrate environmental conditions over long periods of time. They are sedentary, which allows them to be

Figure 19.1: Mexican states where fish-based IBIs have been (light) or are being developed (dark). **Source:** Authors' research results.

used along a continuum. They are abundant and diversified and good colonizers, which allows them to respond to a wide variety of disturbances (Rosenberg/Resh, 1993). These characteristics make macroinvertebrates good indicators of pre-existing conditions in aquatic ecosystems.

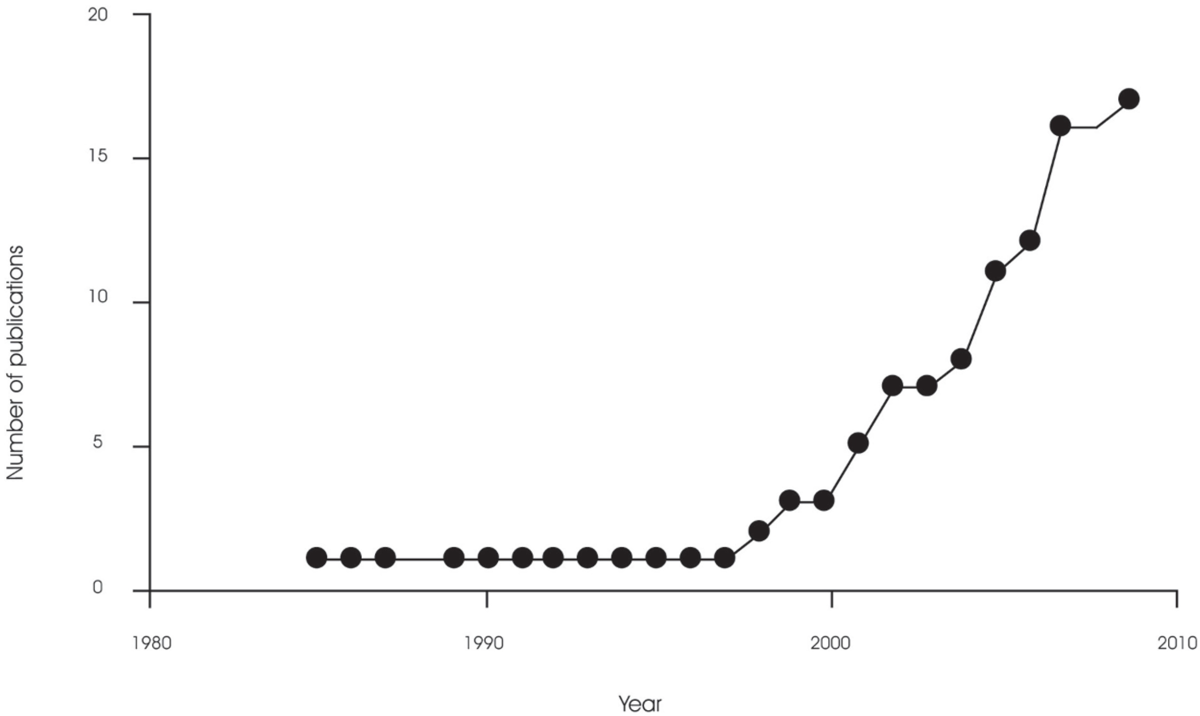
Macroinvertebrates as biomonitoring tools have been used in México since 1985. Since 2000, the use of macroinvertebrates in freshwater ecosystems has rapidly expanded (figure 19.2). Table 19.1 includes the various macroinvertebrate-based indices used in Mexico. In the following lines we also present a summary of the advances that have been made in the use of macroinvertebrates for aquatic biomonitoring during the last 25 years.

Rosas et al. (1985) first used *Beck´s Biotic Index* (BBI) to evaluate the water quality in Lake Patzcuaro. In the BBI, organisms are grouped into three categories: class (1) organisms sensitive to or intolerant of pollution; class (2) medium tolerance organisms; and class (3) organisms tolerant to pollution. After Rosas et al. (1985), macroinvertebrates were not used in Mexico until the end of the 1990s. In 1999 Sánchez Vélez and García Núñez (1999) explained at the Congreso Nacional de Irrigacion the advantage of using macroinvertebrates as bioindicators, and made recommendations for the use of these indicators in Mexico. In 2000 De la Lanza Espino et al. (2000) presented a book on the groups of aquatic organisms and biological indices used in water quality assessment.

The *sequential comparison index* (SCI) developed by Cairns and Dickson (1971) was used by Saldaña Fabela (1998) and Saldaña Fabela et al. (2001) to evaluate water quality in the Pescados River and two tributaries of the La Antigua River in Veracruz. The SCI is based on run theory. In this theory a run is initiated each time that an organism, chosen at random from a sample, is different from an organism previously chosen. The index does not require taxonomical knowledge and is based on visual comparisons of observed organisms.

Santiago Fragoso and Sandoval Manrique (2001) used aquatic beetles as bioindicators in the Cuautla River. They analyzed the habitat condition for each species and used these as pollution indicators. They presented tolerance limits for the species and for other biota. Hilsenhoff's biological index (FBI; Hilsenhoff, 1988) was used by Henne et al. (2002) to evaluate the effect of wastewater from a sugar processing plant in the Ayuquila River basin. They val-

Figure 19.2: The number of articles related to the use of macroinvertebrates as bioindicators for aquatic ecosystems. **Source:** Authors' research results.



idated the index for regional use. The FBI is a modified version of the biological index developed by Hilsenhoff (1982). The index uses indicator taxa. Tolerance values ranging from 0 (sensitive species) to 10 (tolerant species) are assigned to each indicator invertebrate family. This same index was used by Huerto et al. (2005) in the Amacuzac and Balsas Rivers (states of Morelos and Guerrero) and Mathuriau et al. (2010) in the Querendaro, Zinapécuaro, Chiquito, Grande de Morelia, San Marcos and La Palma Rivers located in the Cuitzeo Lake basin.

Following Henne et al. (2002), Weigel et al. (2002) developed and validated the first benthic macroinvertebrate-based IBI for streams in west-central Mexico. This IBI follows a similar structure to a fish-based IBI. Weigel et al. (2002) uses the following metrics: catch per unit of effort, generic richness, percentage abundance of Ephemeroptera, Plecoptera and Trichoptera, percentage abundance of Chironomidae, Hilsenhoff's biotic index, percentage of organisms living in a deposition zone, percentage of predator organisms, and percentage of collector organisms.

Perez Munguia (2007) developed a coleopteran-based IBI (IIBACA) for karstic springs in the Huasteca region. He used eight metrics to evaluate water quality: taxa richness, taxa density, number of sensitive taxa, percentage of omnivore/collector taxa, percentage of predatory taxa, proportional abundance of grazing and filter-feeding collector taxa, number of sessile taxa, and proportion of sessile taxa. Based on the IIBACA, Pérez Munguía and Pineda López (2005) developed an IBI based on macroinvertebrates (IIBAMA) for streams and rivers in central Mexico. The metrics they used included: richness of Ephemeroptera, Plecoptera and Trichoptera, tolerant insect richness, intolerant species richness, mean site tolerance, and total sessile taxa. Pérez Munguía et al. (2006) validated the IIBAMA and compared it with the French IBGN (AFNOR, 1992) and with the *visual environmental quality index* (ICAV; Barbour et al., 1999) used to describe physical habitat. This index was applied to several other basins in central Mexico (Peréz Munguía, 2007).

Also in 2005, Hurtado et al. (2005) studied the structure and ecological changes in the macroinvertebrate community of the San Juan River (states of Hidalgo and Queretaro). They used diversity and similarity indices and made suggestions for the design of biological conservation strategies.

López Hernández et al. (2007) used the *Extended Biotic Index* (IBE; Ghetti, 1986) to evaluate water quality in 11 sites located in the Lerma River. The IBE is a modified version of Trent's Biotic Index (Woodiwiss, 1964). This tool uses the identity of families, genera

Table 19.1: Macroinvertebrate-based indices used in Mexico to evaluate environmental quality in freshwater ecosystems. **Source:** Authors' research results.

Indices	Author index	Indices used by
Diversity indices		
Shannon-Weiner's index (H´)	Shannon/Weaver (1949)	Rosas et al. (1985), Huerto et al. (2005), Pérez-Munguía (2007)
Brillouins's index	Brillouin (1951)	Huerto et al. (2005), Hurtado et al. (2005)
Evenness index	Pielou(1966)	Huerto et al. (2005), Pérez Munguía (2007)
Simpson's index	Simpson (1949)	Huerto et al. (2005), Hurtado et al. (2005),
Sequential Comparison Index (SCI)	Cairns/Dickson (1971)	Saldaña Fabela (1998), Saldaña Fabela et (2001)
Similarity & dissimilarity indices		
Jaccard's index	Jaccard (1908)	Huerto et al. (2005), Hurtado et al. (2005)
Taxonomic distinctness index (*)	Warwick/Clarke (1995)	Campbell and Novelo Gutierrez (2007)
Biotic indices		
Beck Biotic Index (BBI)	Beck (1955)	Rosas et al. (1985)
Family Biotic Index (FBI)	Hillsenhoff (1988)	Henne et al. (2002), Huerto et al. (2005), Mathuriau et al. (2010)
Extended Biotic Index (IBE)	Woodiwiss (1964) modified by Ghetti (1986)	López Hernández et al. (2007)
Indice Biologique Global Normalisé (IBGN)	AFNOR (1992)	Pérez Munguía et al. (2006)
Visual index	http://www.iwla.org/	Campbell (2007)
Multimetric indices		
Index of Biotic Integrity (IBI)	(Karr 1981)	Weigel et al. (2002), Pérez Munguía and Pinada López (2005), Pérez Munguía et al. (2006), Pérez-Munguía (2007); Pérez-Munguía et al. (2007)

and species which are entered in a two-way matrix where lines correspond to faunal groups and units, and columns refer to the total number of units encountered in the collections.

Also in 2007, Campbell and Novelo Gutiérrez (2007) used an index developed by Warwick and Clarke (1995) to assess the environmental impact of the construction of a reservoir in the state of Hidalgo. This tool uses the *taxonomic distinctness index* and is based on odonates and the phylogenetic distances between species.

Campbell (2007) reported on an initiative to involve local communities in monitoring environmental quality in the Pixquiac River (Veracruz). A simple index developed by the Izaak Walton League of America (<http://www.iwla.org/>), which uses visual macroinvertebrate identification techniques adapted by Global Water Watch, was implemented in this basin to empower local communities in the management of their natural resources. Finally, at the federal level CONAGUA mentioned in their 2008 Estadísticas del Agua en Mexico that biological monitoring tools were being used to evaluate water quality in several regions of Mexico.

All macroinvertebrate-based biological monitoring tools have been used in ecosystems located in central Mexico (in 12 states; figure 19.3). There is no information on the use of such tools in southern and northern Mexico. However, there is increasing interest in

Figure 19.3: Mexican states where macroinvertebrates have been used for biological monitoring of aquatic ecosystems. **Source:** Authors' research results.

developing and using these tools in the state of Nuevo León (Quiroz Martínez/Rodríguez Castro, 2006).

19.6 Discussion and Perspectives

As in most Latin American countries, the use of fish and macroinvertebrates as biomonitoring tools is in its infancy. Literature is sparse (26 articles), and deals only with surface waters. The low number of articles may reflect a lack of interest in the study of the functioning of Mexican freshwater ecosystems (Sarma, 2008). However, an exponential increase in the number of biomonitoring-related articles has occurred recently (figure 19.2). A possible explanation for this trend is the recent arrival in Mexico of researchers who have been trained in the use of these techniques abroad. Also, the increased collaboration between CONAGUA and the *Mexican Institute for Water Technology* (IMTA) in the development of simple-use monitoring tools has allowed multiple research groups to begin the development of these tools (Saldaña Fabela, personal communication).

The current trend in Mexico is for the development of indices to evaluate the biotic integrity of aquatic ecosystems. Other methodological approaches, such as predictive models, can be used, which compare community composition between impacted and reference sites. These predictive models are based only on the taxonomic composition of communities found in collection sites. The impact is measured by the loss of taxa in degraded sites, taking reference sites as a baseline. This method has been used in Canada (*Benthic assessment of sediment*; BEAST; Reynoldson et al., 1995), the United Kingdom (River invertebrate prediction and classification system [RIVPACS]; Wright et al.. 1993), and Australia (*Australian river assessment system*; [AUSRIVAS]; Parsons/Norris, 1996).

Another alternative is the use of methods that incorporate the functional integrity of aquatic ecosystems via the analysis of biological and ecological attributes of taxa. Life histories, morphology, physiology and ethology, habitat use, and environmental preferences can be used (Charvet et al., 1998). In a method that incorporates these attributes, the *River Habitat Template* (Townsend/Hildrew, 1994), habitat is the central element which determines biological attributes and dictates species adaptation. Biological and ecological attributes quantify functional specificity (nutrition, dispersal, respiration, etc.) of each taxon. An advantage of these methods is that functional groups respond in a predictable fashion to anthropogenic effects.

All of these methods require the comparison of communities between 'pristine' sites and degraded sites. This is one of the most important limitations in Mexico, as it is becoming increasingly difficult to find ecosystems without human impact that can function as reference sites. Another limitation is the lack of information on the taxonomy and ecology of numerous fish species and macroinvertebrates in several regions of Mexico. It is thus necessary to generate basic knowledge on the biology of aquatic communities, and to conserve as many 'pristine' sites as possible.

Biomonitoring techniques are not currently included among the approved water evaluation methods by the Mexican government. Only physico-chemical and microbiological indicators are included. It is expected that, if the use of biological monitoring methods by academics and government officials increases, they could be incorporated in standardized environmental monitoring protocols. This is currently the norm in several areas of the U.S., Canada and the European Union. Method standardization is required to achieve successful implementation at a national level.

In addition, the use of such biological tools in volunteer community-based biomonitoring is an important alternative in rural communities where physico-chemical assessments are unavailable. It also allows local communities to gain better management of their natural resources as they are able to detect any changes occurring locally more rapidly. This, along with training and certification, would empower local communities in the decision-making process for natural resource management.

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20 Configuration of a Hydrocarbon Contamination Plume and Restoration of a Site near Reynosa, Tamaulipas

Salvador Israel de la Garza González and Raúl Herrera Mendoza

20.1 Introduction[1]

The semi-arid climate of the north-east of Mexico requires careful management of water resources in order to satisfy the demands of the population from the limited supply of groundwater resources in the region. These water resources are vulnerable to accidents or spills of hydrocarbons in places of collection, transport, or storage of combustibles, such as gas, petroleum, or derivatives. When a leak is detected in a pipeline or storage tank, precise mitigation steps are taken to eliminate potential sources of contamination of soil and groundwater and, in accordance with relevant Mexican standards, studies are undertaken to evaluate the affected sites, to determine the extent of contamination, and to select and implement the appropriate technology for restoring the contaminated site.

Such activities in Reynosa, Tamaulipas involved an environmental-geological evaluation of the contamination plume in the vicinity of a closed hydrocarbon storage site that lacked the means to contain the spill. For this task, subsurface physical, topographic, geologic, and stratigraphic studies were conducted on the area. The techniques applied focused on the lithology, stratigraphy, rock fracturing, subsurface resistivity, and physical and hydraulic properties of the aquifer. Piezometric and hydrochemical properties of the spilled fluid and its concentration and distribution in the soil and groundwater were examined.

The results of the study were used to construct a model of the contamination plume in which, in accordance with the geological and stratigraphical character of the site, two subsurface layers with different permeabilities were identified. The first, more permeable, layer extended two or three metres below the surface, defining the zone saturated by hydrocarbons, as was also confirmed by chemical analysis. With increasing depth the permeability decreased considerably. The hydrocarbons penetrated through the desiccation cracks causing the aquifer to spill. In this second zone hydrocarbons were present in a very low concentration.

The investigation illustrated that the plume covered 4.6 hectares with a zone of saturation due to high permeability. Through the desiccation cracks in the upper layer of the aquifer an 8 metre long supernatant zone, diluted with hydrocarbon, was detected. After the size and shape of the plume were determined, the contaminated soil was placed in biocells for bioremediation. For cleaning the aquifer, the diluted hydrocarbon and supernatant were extracted and processed in a treatment plant especially designed for the site. Finally the treated water was reinjected into wells above the aquifer to reduce its over-exploitation.

These techniques are vital for north-eastern Mexico, where there are intensive activities of extraction, transportation, and storage of gas and derivatives that often cause accidents in the physiographic province of the Burgos Basin, a part of the state of Tamaulipas.

Research into the processes related to and the evaluation of contaminated aquifers offers results that optimize sanitation technologies and their application around the world. This theme is a starting point for the evaluation and sanitation of aquifers affected by different sources and contamination events (IMTA, 2000).

20.2 Background

As an important part of the operation, which includes the extraction, storage and transportation of hydrocarbons in the basin of Burgos, a series of infrastructures are necessary for the optimal operation of gas

1 Keywords: Hydrocarbon contamination, contamination plume, bioremediation, biotreatment cells, groundwater treatment plant.

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and condensate facilities; these can reduce environmental risks and meet ecological regulations for affected sites.

These activities started in 1998, when 18 different sources of pollution were detected, among them two critical sources, a dam and a storage area of hydrocarbons which directly affected the soil and the aquifer. Between 1998 and 2003, different companies and institutions made evaluations, and in 2004 the *Corporación Mexicana de Investigación en Materiales* (COMIMSA), S.A. de C.V. began its evaluation and remediation of the affected soils and aquifers.

20.3 Objectives

The project focused directly on three main objectives for restoring the affected site by approaching the original conditions of the environmental surroundings:

- to establish the geological and hydrogeological conditions of the site that produced the configuration of the contaminated plume which affect the soil and aquifer;
- to analyse restoration technologies and to select the technologies that would achieve the best results for the specific conditions of affected sites; and
- to apply the selected technologies to remediate the soil and aquifer.

20.4 Regional Geology and Hydrogeology

With the Laramidic Orogeny event in the late Cretaceous, the uplifting of sedimentary sequences caused large structural folds which consolidated the Sierra Madre Oriental mountain range (Michalzik, 1988). This caused the development of basins with a parallel orientation to the fold belt, giving rise to the Burgos Basin, where the palaeo-elements of the Tamaulipas Peninsula and of the San Carlos Island served as its western limit. During the Tertiary Period this caused a focus for sediment deposition, where the total Cenozoic sedimentary column reached thicknesses of approximately 10,000 metres (Echánove, 1986).

The sediments in the basin of the Cenozoic rocks describe a series of stripes that extend up to the coast line with a general orientation NNW-SSE decreasing in age from the west (Palaeocene) to the east (Miocene) and with sporadic outcrops. Above the Tertiary rocks a powerful, thick level of alluvial sediments is located, primarily consisting of chalky sandy soil and limy sandy soil, interlinked with horizons and recent conglomerates of gravel and thick sand with a calcareous matrix.

The regional hydrogeological units comprise several deep semi-confined and confined aquifers (Werner, 1996), which are limited by sediments, clay rocks, and sandstones that prevail in the Cenozoic stratigraphic column. There are also semi-confined shallow aquifers, with sandy soils and conglomerates that are heterogeneously distributed in alluvial plains, differing in permeability due to the clay content and enrichment by calcium carbonate.

The general direction of the flow is towards the north-east and east for the main surface water currents of the region, such as the Rio Grande (INEGI, 1986), which is less than 10 km away to the north-east, and in a straight line towards the east about 100 km from the coast of the Gulf of Mexico.

20.5 Location of the Site

The affected site is located about 13 km south-west of the city of Reynosa in Tamaulipas, between latitude 25° 58' 30" and 25° 59' 15" north and longitude 98° 15' 00" and 98° 15' 25" west. The site is best and directly accessed from kilometre 108 of the federal highway 97 Reynosa-San Fernando that extends 2.5 km towards the south-east along the path of the Ejido La Retama (figure 20.1).

20.6 Methodology

To achieve the objective, a methodology was designed for evaluation and restoration of the affected site:

1. *Analysis of information*, through the compilation of the history of the site, previous studies, internet information, published notes in journals, drawings, etc., as well as field visits to the areas of extraction, storage, and transport of hydrocarbon in the vicinity.
2. *Evaluation of the contaminated site* and polluted aquifer by examining the physical properties of the environment, the degree to which it was affected, and the extension of the plume of contamination through analyses focusing on the:
   a) *geology of the site* in order to understand its rock and sediment formation as well as the existing planar structures, to develop the

Figure 20.1: Location of the study area. **Source:** By the authors.

stratigraphy and structural elements that may alter the flow and infiltration of the hydrocarbons into the subsoil;

b) *hydrogeology* in order to determine the type of aquifer, the direction of the groundwater flow, the dynamic of the phreatic water level and the extension of the floating hydrocarbons in the water. Also, groundwater samples were taken and analysed for their TPH (*Total Petroleum Hydrocarbons*) and BTEX (*benzene, toluene , ethylbenzene, xylenes*) content in order to identify the type of hydrocarbons, and their concentrations dissolved in water to comply with the official Mexican standard (NOM-127-SSA1-1994, modified in 2000; Secretaría de Economía, 2005) and international standards (ASTM, 1997). Laboratories certified by the *Entidad Mexicana de Acreditación* (EMA) analysed these samples. The construction of the extraction wells in the strategic locations was in line with the hydrodynamic features of the aquifer (CONAGUA, 1994a, 1994b), in order to understand the flow and permeability. These pumping tests allowed the implementation of a model of extraction for the contaminated water and hydrocarbon;

c) *geophysical prospection* was determined indirectly through the geological units and an analysis of the strata with possible hydrocarbon contamination, because of the limitations of resistivity methods for the detection of hydrocarbons in the subsoil (Lesser/Saval, 2004). A series of resistivity images was scheduled, with probes in profile paths that were strategically distributed throughout the field, allowing wide area coverage with the greatest potential of contamination, taking into account the variation of resistivity values of the contaminated soil and subsoil (Shevnin et al., 2004). These data permitted an indirect delimitation of the contamination plume;

d) *characterization of the site* by selecting strategic points for drilling and sampling of the soil in accordance with the standard NOM-138-SEMARNAT/SS-2003 (PROFEPA, 2005). In addition, infiltration tests in situ and soil tests detected the permeability, the hydraulic conductivity, and the infiltration rates associated with the upper stratum of the aquifer and its behaviour with infiltrated or leached pollutants at the surface and at the phreatic level. As well as this, the characteristics of the soil were analysed with the *Unified Soil Classification System* (USCS);

e) *a kinematic simulation of the contamination plume* was developed to simplify the analysis and to supply a tool for characterizing and evaluating alternative situations to assist in making decisions about the restoration of affected sites. Another goal was to determine the movement of the contamination plume in the unsaturated zone and in the shallow part of the aquifer.

3. *Selection of restoration technologies*, based on the results from the evaluation phase, for restoring the polluted sites.
4. *Application of selected technologies* for restoring the saturated soil, which had been the main source

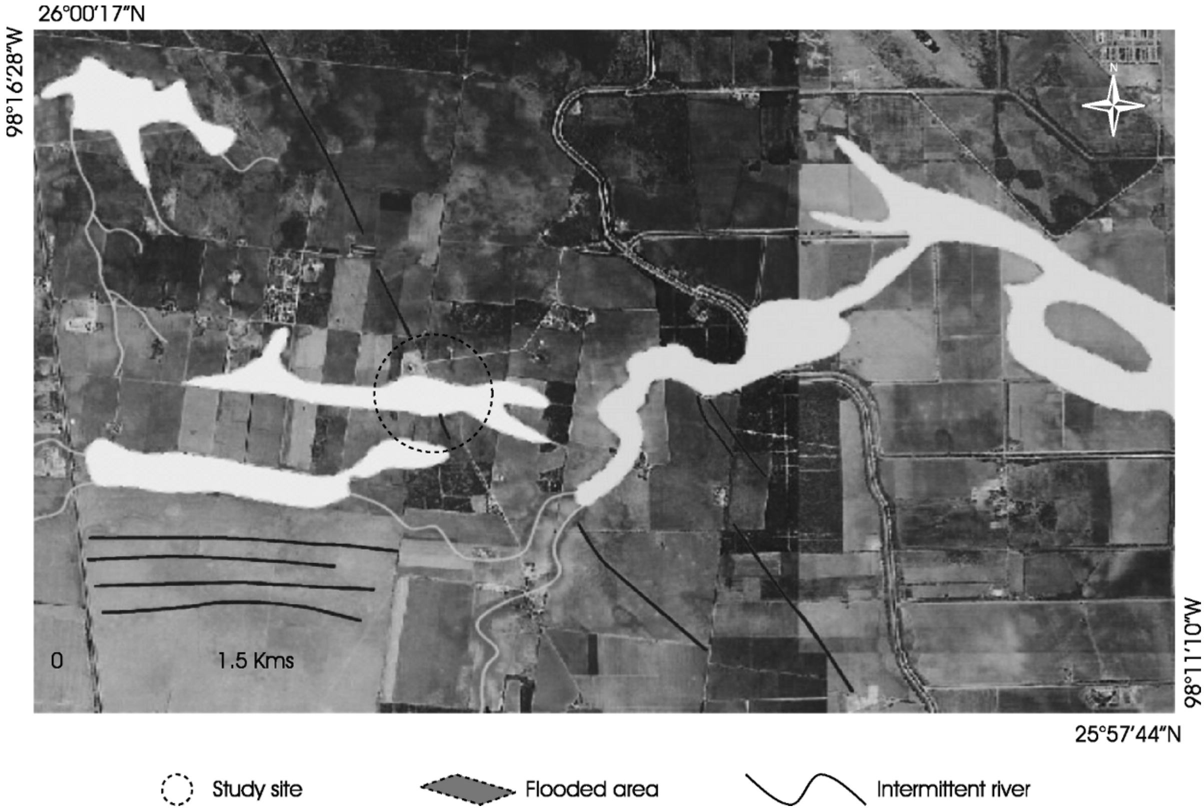


Figure 20.2: Location of existent wells in the study area. **Source:** By the authors.

of pollution of the aquifer by hydrocarbons, and the deployment of a mobile treatment plant for the contaminated extracted water.

20.7 Results

20.7.1 Analysis of Information

Little information was obtained from previous evaluations based on 4-year-old piezometric maps and stratigraphic columns of the monitoring wells. Field trips explored the physical status of the infrastructure for restoring the site and monitoring the aquifer. As no monitoring of the wells existed, a video was made in 4 wells and widely distributed in the area. This showed that the protective casing of the wells was inadequate as the phreatic level was over the grooved tube, practically in a screen without a groove. This prevented a connection between the top of the aquifer and the well, thus calling into question the presence or absence of floating hydrocarbons in the water.

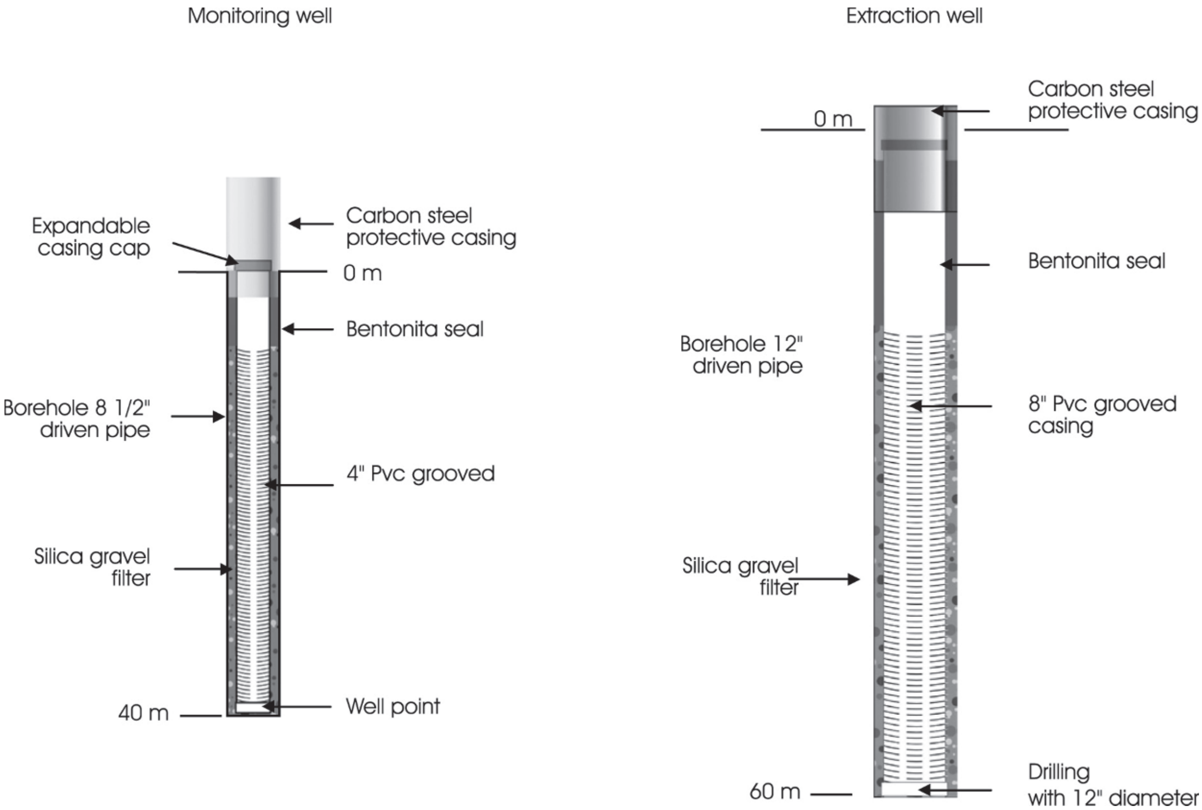
20.7.2 Evaluation of the Contaminated Site

20.7.2.1 Local Geology

Information from existing boreholes of more than 100 metres indicated that the upper Oligocene rocks consist of formations of Frío No Marino and Norma Conglomerate located at a depth of more than 80 metres. Thick alluvial sediments overlay these rocks; these consisted of a chalky sandy soil with a rich content of calcium carbonate, which consolidated horizons at depth. The landscape, with smooth hills, consists of alluvial chalky sandy soil with sporadic calcium carbonate outcrops from the Quaternary and an absence of complete rock outcrops near the site.

In the Burgos Basin a series of deltaic systems emerged, showing extensive deformation due to numerous primarily normal faults (Flick/Quade, 1981). These faults or fractures are not on the surface, but they are covered by stratigraphic post-deposed discontinuities, found in the oldest lithological units. Formlines manifest themselves along a NW-SE direction and are parallel to linear structural elements such as axes of the folds that may correspond to deformation fractures, as the most prevalent in the region. Form-

Figure 20.3: Design of the monitoring and extraction wells built on the affected site. **Source:** Developed by the authors.



lines are also manifested in a N-S direction, oblique to the first, apparently corresponding to shear fractures.

In particular there is a wide formline with a NW-SE direction, crossing directly through the eastern portion of the affected site and parallel to a surfaced road. To find the evidence of these formlines in the field it is impossible to distinguish them directly, because of the sedimentary cover that makes up the topographic relief. Thus, they can only be analysed with aerial photographs or satellite images.

Some flood areas were located and plotted by intermittent water flows on the surface in that area. One of the zones directly affects the southern portion of the region and aligns in a W-E direction, where the water flows eastward (figure 20.2).

20.7.2.2 Hydrogeology

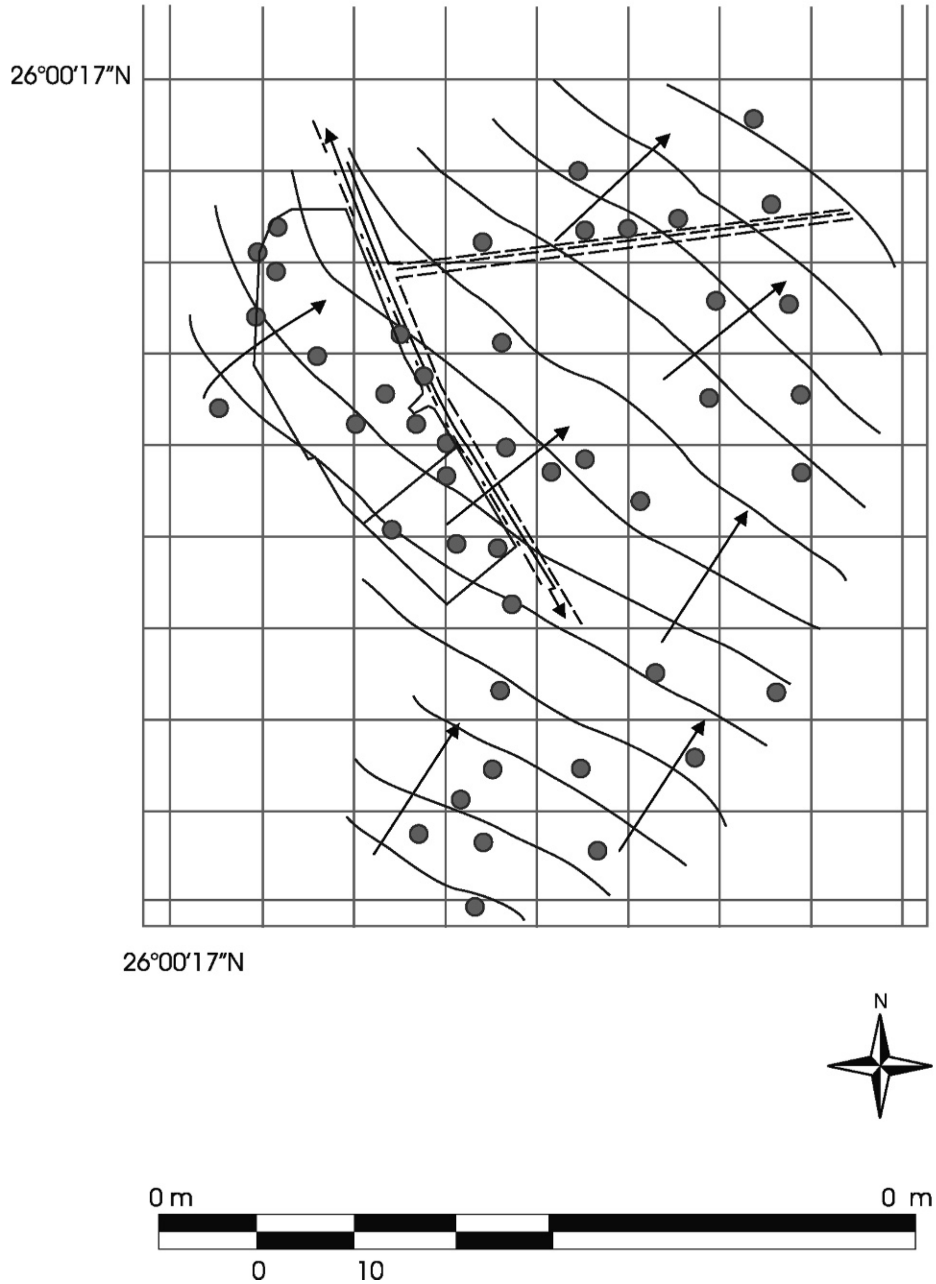
Given the characteristics of the sediments found in the area, the hydrogeological units refer to a shallow aquifer, where the groundwater levels oscillate between 15 and 20 metres deep. The levels are measured in wells near the site, where the regional recharge of the aquifer originates and a local infiltration will exist when pluvial precipitations occur. The arrangement of the carbonate horizons is important for the semi-confinement and permeability of this aquifer (Custodio/Llamas, 1996).

Piezometric measurements and the 60 geo-referenced monitoring wells have shown gaps in the registered altitude, in the depth of the phreatic level, in content, in the thickness of the hydrocarbon, and in the total depth of the wells. According to the piezometric analysis, the groundwater flows to the NE (figure 20.3), where the water moves with the regional flow and with a hydraulic gradient difference of 2 metres in the direction of the Rio Grande a few kilometres away.

The preliminary analysis of TPH and of the BTEX chemical compounds was made for 14 groundwater samples from wells with evidence of hydrocarbon concentrations. These results indicate that the predominant concentration corresponds to a half fraction of TPH (diesel-range), with values up to 828 mg/l; a high content of benzene and xylene was found, with concentrations up to 1,289 and 893 g/l respectively.

For industrial use no standards exist for hydrocarbons dissolved in water. Following the established standards and the National Water Law of Mexico and its regulation (CONAGUA, 1994), for this study the official Mexican NOM-127-SSA1-1994 was taken; this

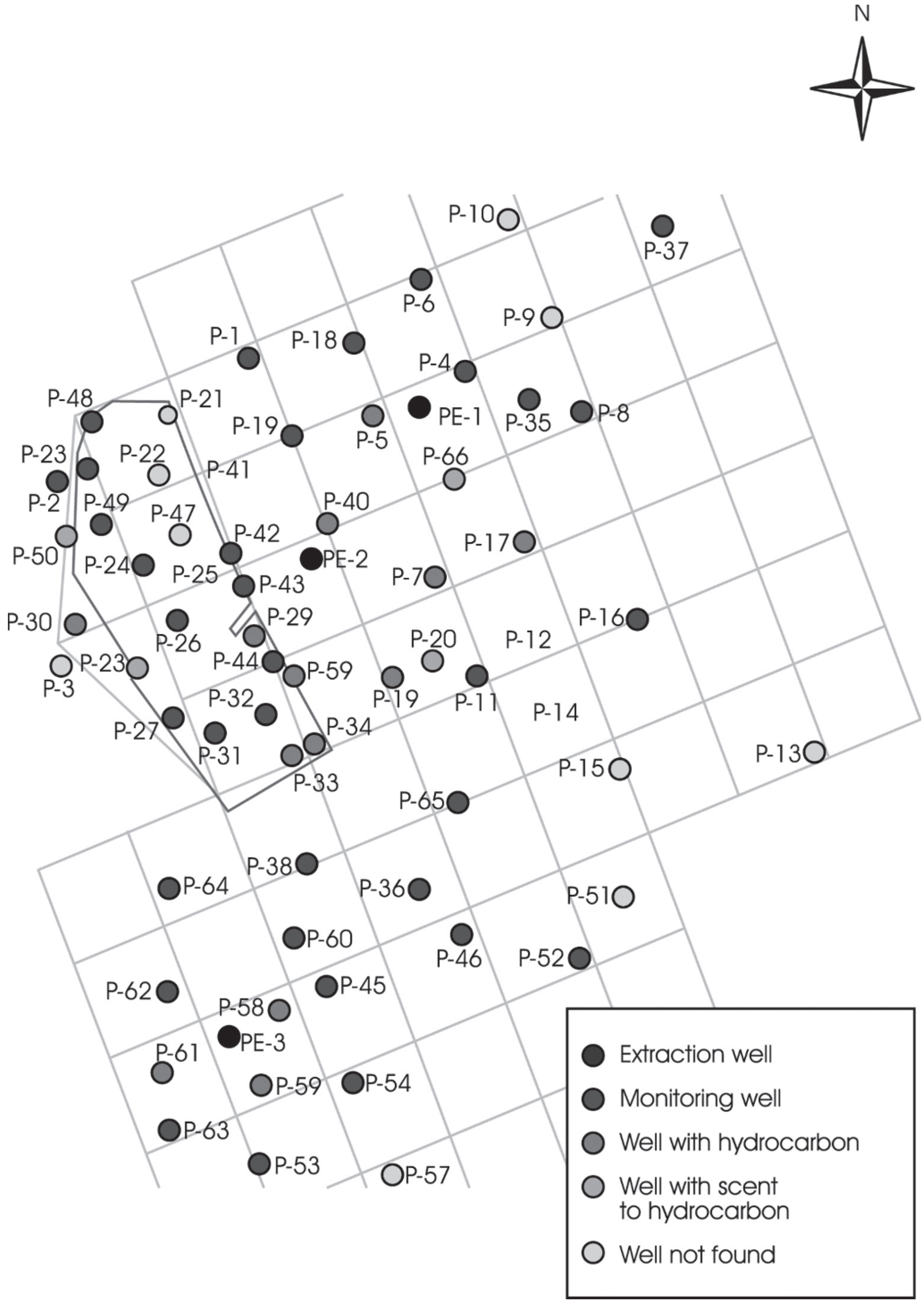
Figure 20.4: Piezometry of study area, arrows indicate the direction of the flow of the groundwater. **Source:** Results from the research by the authors.



indicates permissible limits of BTEX for human consumption of up to 10 g/l for benzene and 500 g/l for xylene.

Based on the field evidence and its results, three extraction wells and six monitoring wells were constructed in the direction of the groundwater flow. The six monitoring wells had boreholes 40 m in depth with a diameter of 8½ inches, a PVC grooved casing with a diameter of 4 inches, a well point, an expandable inner casing cap, a gravel silica filter in the annular space with a bentonite seal, and a carbon steel protective casing. The three extraction wells, R1-E1, R1-E2, and R1-E3, each had a borehole of 12 inches in diameter, a grooved casing 8 inches in diameter, a well point, an expandable inner casing cap, a gravel silica filter in the annular space with a bentonite seal ,and a carbon steel protective casing (figure 20.4).

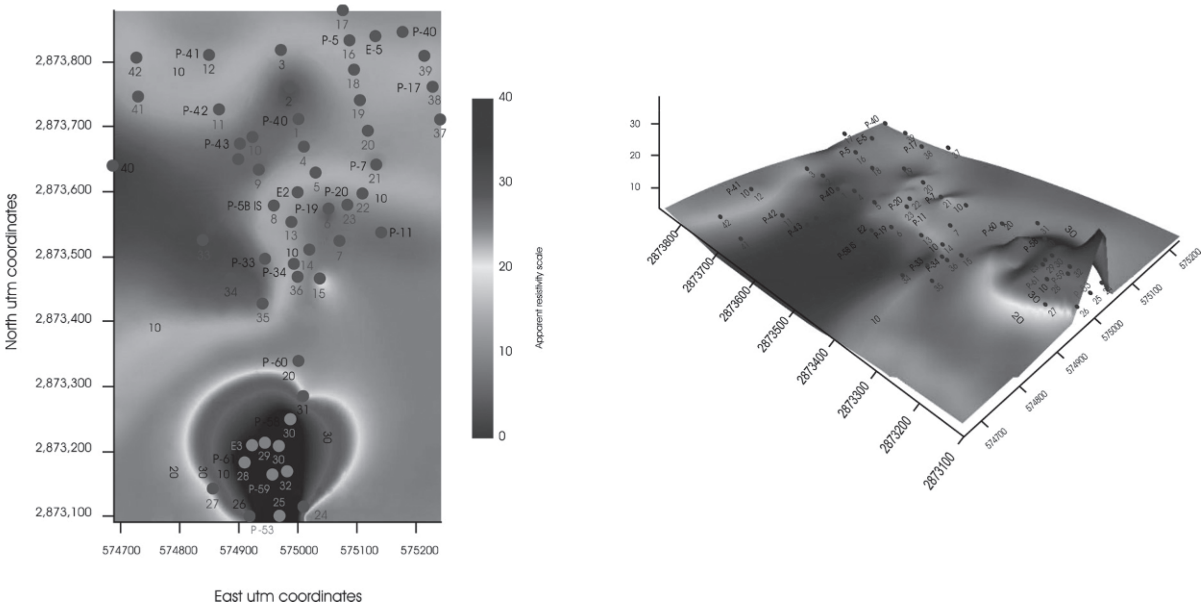
Figure 20.5: Location of the existing wells in the study area. **Source:** Developed by the authors.



These wells are part of an existing monitoring network in the affected area that complements a total of 66 wells (figure 20.5).

Examining the lithology of the borehole of 60 metres in depth, in the first five metres was found an inter-bedded horizon column of soil with sand, clay and silt content, and some calcium carbonate concretions. Drilling deeper, a consolidation of the soil was observed with silty soil and a carbonated cementant. Below 15 metres, a humid zone began, which was saturated two metres lower, indicating the beginning of a leaky aquifer with limited water contribution.

Figure 20.6: Resistivity anomalies of the affected site, units located at depth of 20 metres and layers containing hydrocarbon. **Source:** Results from the research by the authors.



The horizon with the carbonated cementant behaves in a similar way and has a low water contribution until it reaches a depth of 56 metres, where a thick and consolidated bed of calcium carbonate was fractured, allowing a higher water contribution to flow upwards to 16 metres. This indicates the presence of a confined aquifer.

A pumping test was made for each extraction well and the results were as follows:

- In well R1-E1, the extraction started with a pumping rate of 4.5 l/s that lasted for the first 10 minutes, then the performance decreased to 4 and 3.4 l/s and the flow stabilized at 3.8 l/s. The abatement was constant and levelled off at 27 metres after 3 hours of extraction. This made it possible to install the pumping equipment to a maximum depth of 30 metres with a maximum performance of 3.8 l/s.
- In well R1-E2, the extraction started with a pumping rate of 5 l/s and decreased until it stabilized at 3.6 l/s. The draw-down of the water levels was constant at 27 metres within 4 hours of extraction, which made it possible to install the pumping equipment to a maximum depth of 30 metres with a maximum pumping rate of 3.6 l/s.
- In well R1-E3, the extraction started with a pumping rate of 10 l/s with 2 hours of constant flow. Later, the pumping rate decreased and stabilized the flow at 6.2 l/s. The draw-down of the water levels was constant and levelled at 27 metres after less than 2 hours of extraction. This made it possible to install the pumping equipment to a maximum depth of 30 metres with a maximum pumping rate of 6.2 l/s.

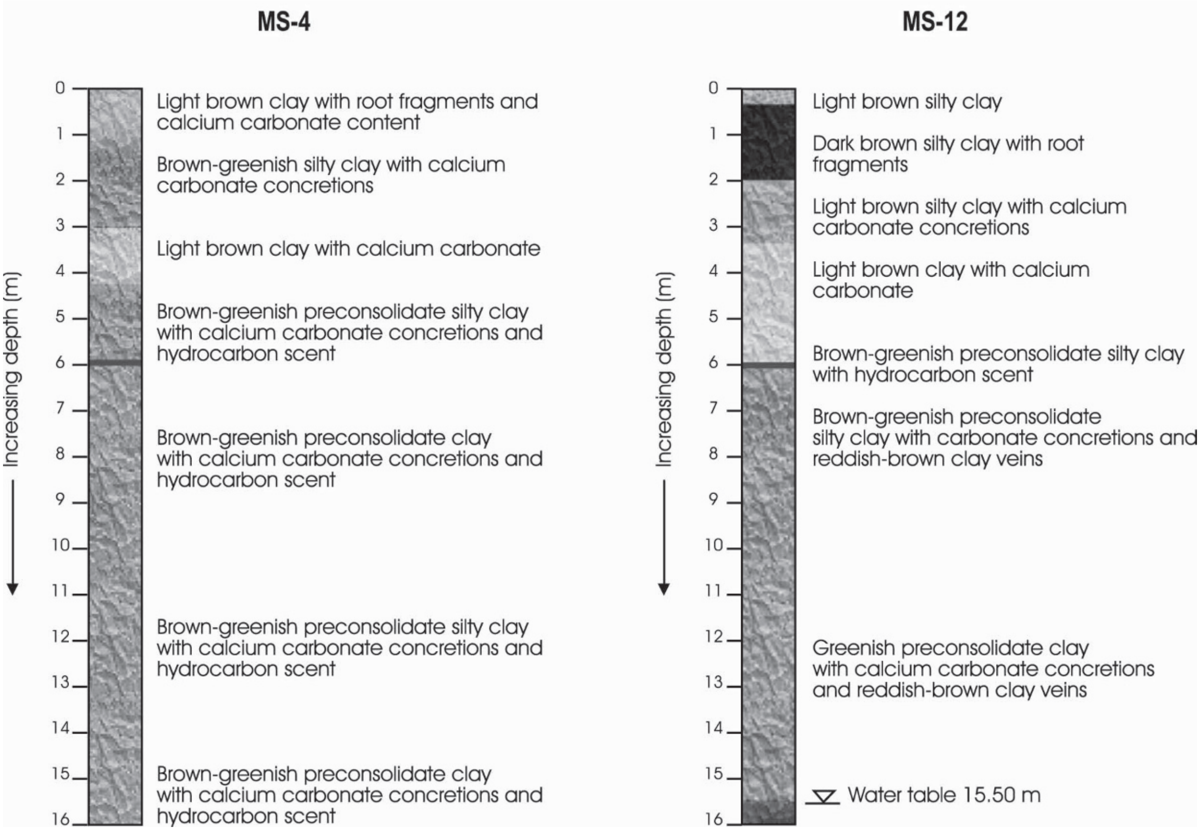
Based on the drilling and pumping tests, the results demonstrated the existence of an aquifer system that was composed of an aquitard (Werner, 1996), with small contributions of water and extremely low flows, found in a column between 15 and 55 metres. Below 55 metres, a calcium carbonate layer was fractured; this confined a major flow to the upper layer of the aquifer up to 15 or 20 metres due to pressure differentials, and it is this aquifer that supports the necessary flow of the contaminated groundwater and the extraction of the hydrocarbons.

20.7.2.3 Geophysical Prospecting

Geoelectrical units associated with the resistivity imaging field probes indicate a subsoil with anomalies in the first 20 metres (figure 20.6), where the unit C1 (blue colour) is associated with terrigenous deposits able to retain hydrocarbon.

The maps of apparent resistivity allow a qualitative interpretation. The profiles are presented with geoelectrical sections to permit interpretation and quantitative integration. The map corresponds to an apparent resistivity depth of AB/2 = 20 m. In this map the saturation zone of the groundwater is located where an important geophysical anomaly was observed in

Figure 20.7: Stratigraphic description of MS-4 and MS-12 sampling points. **Source:** Results from authors' research.



the north-west of the study area, illustrated in blue; this was associated with the presence of clay minerals that can be correlated with sandy chalky sediments with a high concentration of water-saturated minerals impregnated with hydrocarbons.

Around 10 geoelectrical units, associated with stratigraphic units of various thicknesses (denoted as C1), a clay and/or sandy-clay water-saturated deposit with high mineral concentrations was detected, displaying a resistivity of 1 to 8 ohms-metre. The plume configuration of this geophysical unit is irregular. The contamination plume occupied an area delimited by lines drawn from the centre to the south near monitoring wells 33 and 34; to the north near wells 42 and 23, and to the east near wells 5, 7 and 17. This resulted in an affected area extending to 4.6 hectares.

20.7.2.4 Characterization of the Site

The purpose of this activity is to determine the TPH and BTEX concentrations in order to delimit the saturated portion of the contamination plume in the soil. A further goal is to establish the hydraulic conditions of the subsoil such as permeability and capacity for infiltration. Finally, the objective is to obtain the physical parameters such as texture, structure, density, consistency, and colour, and to determine the grain size of the subsoil by granulometric analysis.

Soil sampling and analyses at 1 to 16 metres depth were carried out using a Shelby-type sampling tube for standard penetration testing. Soil analyses were obtained using EPA 8260 and EPA 8015 B methods, determining BTEX and TPH light and medium fractions, to be compared with Mexican standard NOM-138-SEMARNAT/SS-2003. The results show a high concentration of TPH light fraction sites, with data values of 2454 mg/kg, and a medium fraction with data values of 8012 mg/kg, compared with the Mexican standard for industrial soil use which accepts a maximum of 500 mg/kg for light fraction and 5000 mg/kg for a medium fraction.

The highest concentration of hydrocarbons was found three metres below ground, gradually declining with depth until it reached the water table, where floating hydrocarbons again appeared. To analyse in detail the concentration of hydrocarbons below three metres, a core sample was taken using a drilling rig. In the cores a compact and clayey soil smelling of hydrocarbon was found, with drying cracks less than 5 mm thick that connected the surface to the aquifer. A representative stratigraphic column of two sampling points is shown in figure 20.7.

For 14 boreholes, *in situ* tests of infiltration were made to 16 metres. Permeability for the upper layer showed values between 0.65 X 10^{-3} cm/sec and 32.5 X 10^{-3} cm/sec, corresponding to low and medium permeability. However, a lower lithological unit was also identified, with values ranging from 0.39 x 10^{-5} cm/sec to 4.15 x 10^{-5} cm/sec, corresponding to low and very low permeability. In laboratory porosity tests of cores, soil porosity values ranged from 8.5 to 27.3 per cent.

In relation to the textural classes of the soil, defined by the fine particles of an area, a sandy clay loam texture was found. The granulometric composition, humidity, density, and texture for each sample consisted of well to poor graded sand, and in some layers clayey sandy sediments were present. The consolidation of stratigraphic horizons is greater with depth; the humidity of the samples is between 7.42 and 16.47 per cent and its density varies from 0.57 g/ml to 6.66 g/ml.

20.7.2.5 Kinematic Simulation of the Contamination Plume

The purpose of a simulation model may vary depending on the particular interest in the geographical study site. The objective is to simplify the analysis of occurring problems and to provide a tool for analysis that will characterize and evaluate alternative scenarios so as to provide means for taking decisions about the restoration of the affected site. Another goal is to determine the conditions for the movement and/or mitigation of the hydrocarbon contamination plume, especially in the non-saturated and surface portion of the pore aquifer where data are similar with earlier results, such as soil and aquifer characterization, resistivity image probes, and soil mechanics.

In order to develop this activity, it was necessary to use all field information to reproduce the configuration of the hydrocarbon contamination plume in the soil and in the aquifer of the affected site. A further goal is to develop a simulation of the contaminated zone for a continuous degradation scenario, based on the natural movement of the contamination plume.

Two pieces of software were chosen to model the dispersion of the contaminant, Visual MODFLOW and MT3DMS. The first can run stable and transitional state analyses and has a wide variety of border conditions and input data options. It was used to describe the route that the fluid follows. The second is a three-dimensional model for the simulation of advection, dispersion, and chemical reactions of dissolved components in groundwater systems.

The MT3MDS model uses a modular structure similar to the one used in MODFLOW. MT3DMS is used in conjunction with MODFLOW in a two-step simulation, flow (MODFLOW) and transport (MT3DMS). Put simply, the steps to be taken for a simulation of the contamination plume are:

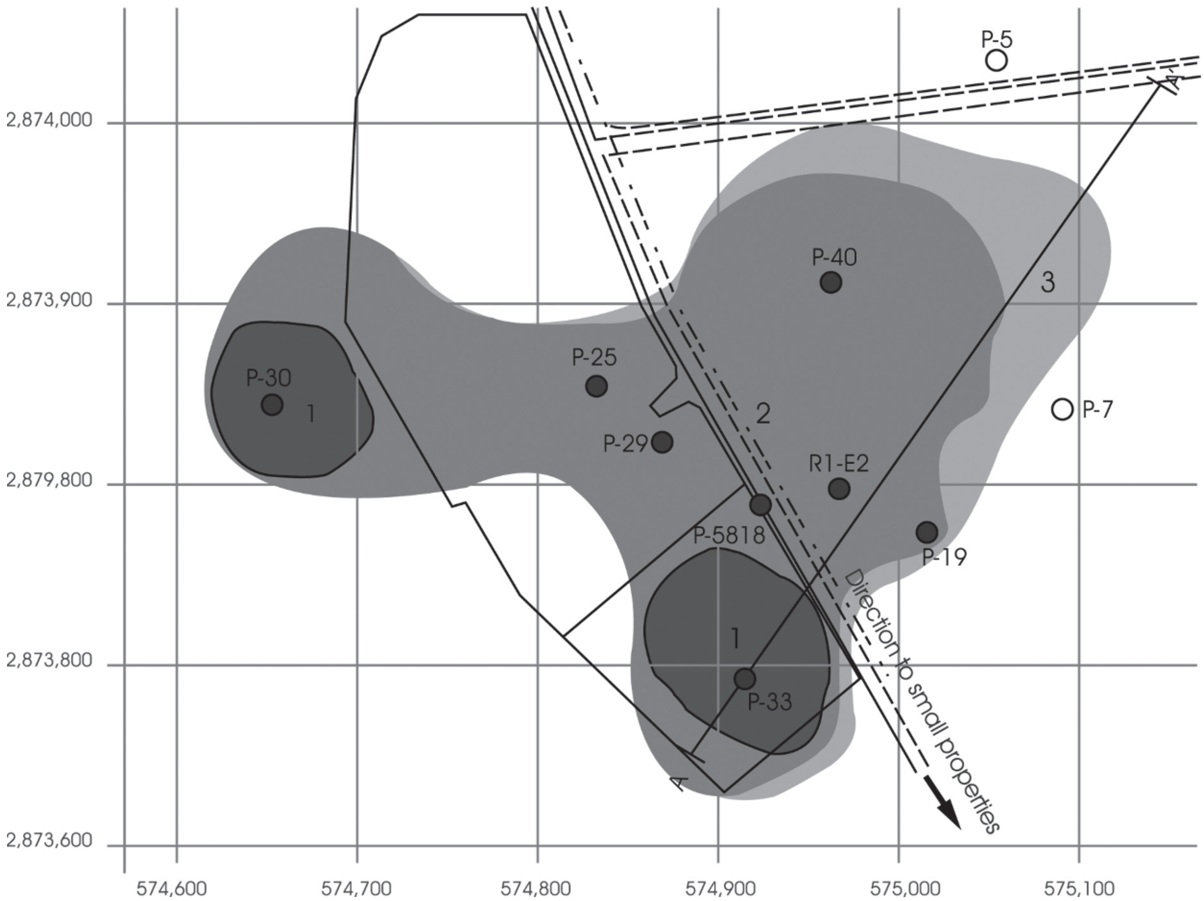
- a conceptual model of the selected area was obtained, including results from topography and boreholes, and that correlated information on the different layers of soil and subsoil;
- a grid of the finite elements in the conceptual model was generated;
- information was integrated with Visual MODFLOW software; the parameters required by the models were hydraulic conductivity, specific storage, porosity, distribution co-efficient, decay constants, etc.;
- boundary conditions of the system were defined; and
- the Visual MODFLOW and MT3DMS models were applied.

Two scenarios of a kinematic simulation of the contamination plume of the area were developed. The first one corresponded with the representation of the contamination plume according to its natural motion, based on current subsurface hydrocarbon contributions caused by the daily operation of oil activities.

Results for this scenario show the movement of the contaminated plume in the east–north-east direction, starting from two main zones corresponding to an old earth-fill dam and a hydrocarbon storage area. The direction of flow is similar to the direction of flow of the groundwater, which indicates the influence of the groundwater flow from the aquifer on the hydrocarbon contamination plume.

In the second scenario, the movement of the contaminated plume is shown for the water and hydrocarbon extraction in well R1-E2. When the extraction activity is included, a change in the dispersion and movement of the hydrocarbon is reflected, decreasing its action and gradually moving towards the extraction, influenced by the cone of depression of the groundwater. This process truncates the normal movement of the contaminated plume and reduces it, intersecting the flow through a cone of depression; this attracts the liquids found in its periphery, with the extraction well being in the centre of the water and hydrocarbon suction.

Figure 20.8: Plan view of hydrocarbon contamination plume with the three observed zones. **Source:** Results from authors' research.



20.7.3 Integration of the Evaluation of the Results

Based on the results of each evaluation activity of the site, the affected area was delimited and characterized. The total surface area was 4.6 hectares and the affected area was 20 metres deep, according to the phreatic level oscillation.

The permeability of the soil horizons was at its highest in the first three metres. With increasing depth and higher calcium carbonate concentrations, the permeability of the layers decreased.

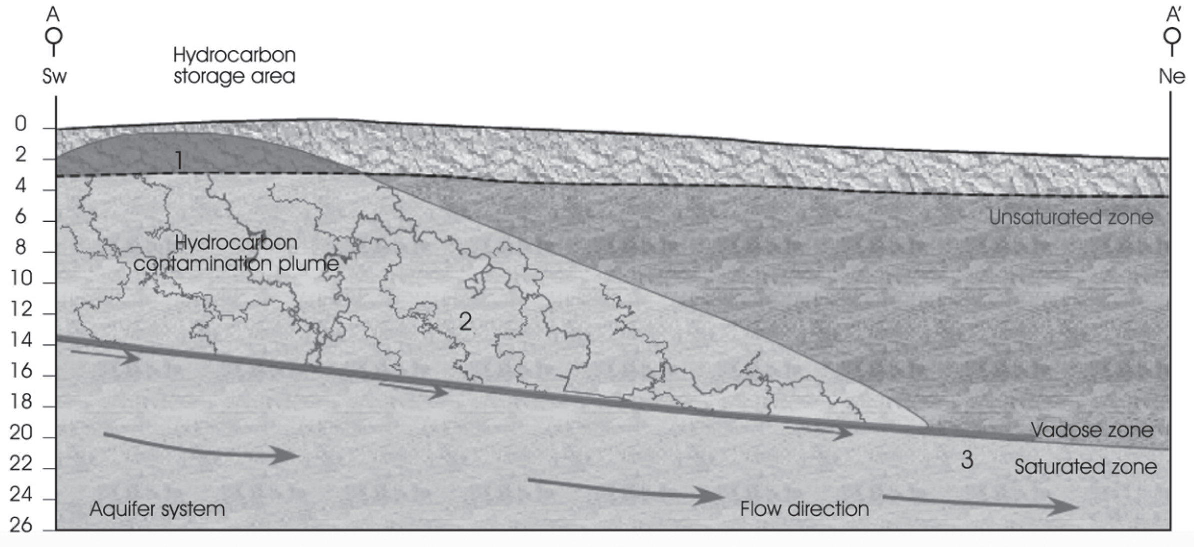
With regard to the configuration of the contamination plume, three sections of the plume were delimited, in areas where the hydrocarbon is stored and transported, according to the permeability, porosity, and depth, among other physical characteristics, of the environment in which the contaminated plume exists (figures 20.8 and 20.9).

The first zone refers to the shallow part of the contamination plume. It extends to the first 3 metres of the subsoil. This is the zone where the hydrocarbon concentrations exceed the permissible limits established by the standard NOM-138-SEMARNAT/SS-2003, where the permeability, transmissivity, and porosity features favour the storage and filtration of hydrocarbons in the most permeable horizon.

The second zone covers the area below 3 metres and above the phreatic level of the aquifer. It is a compact and consolidated subsoil, where the hydrocarbon concentrations are low in most of the area. It has cracks filled with soft sediments and hydrocarbons. Its consolidation does not favour the storing of high concentrations of hydrocarbons, but hydrocarbon leaks into the aquifer through the cracks.

The third zone refers to the aqueous phase of the contaminated plume, which is delimited by the first metre of the aquifer, where the final disposition and dissolution of the hydrocarbons in the water occurs; it contains the extension of the contamination plume. This zone has high concentrations of benzene, tolu-

Figure 20.9: Hydrogeological section showing the three zones of the hydrocarbon contamination plume. **Source:** Results from authors' research.



ene, and xylene, which are dissolved in the groundwater.

20.8 Selection of Environmental Restoration Technologies

Based on the complete results of the evaluation and configuration of the hydrocarbon contamination plume, appropriate technologies may be selected in order to restore the affected site and to obtain efficient results as indicated by the analysis of the evaluation.

Thus the remediation of the first zone of the plume is considered for the first 3 metres of the soil, applying a land-based treatment as part of bioremediation technology, through a process of farming on the site (Piper, 2000). The contaminated soil is removed and placed in a biotreatment cell, then this soil is incorporated into the surface and periodically turned over or tilled to aerate the mixture. Finally, it is returned to the original site, where the soil has already been restored.

For restoration of the aquifer, up to 6 metres with floating hydrocarbons and up to 1.5 metres polluted with BTEX are extracted and processed in a *groundwater treatment plant* (GTP). The clean product is injected into the monitoring wells to prevent overexploitation of the aquifer (figures 20.10, 20.11).

20.9 Implementation of Selected Technologies

20.9.1 Soil Remediation

With this technology 28,700 m^3 of contaminated soil were restored on the surface of approximately one hectare located in the vicinity of monitoring well number 30, where an old earth-fill dam was located, and within the storage area of the hydrocarbons. For the soil remediation a physical demarcation and volumetry of the site was carried out, together with detection and delimitation of the underground infrastructure. The contaminated soil received biotreatment on the site (figure 20.2).

A total of 28,735.10 m^3 of contaminated soil was remedied and returned to its original site after complying with the limits established by standard NOM-138-SEMARNAT/SS-2003.

20.9.2 Sanitation of the Affected Aquifer

The purpose of this activity was to extract the contaminated groundwater and the hydrocarbon in order to restore the aquifer, to quantify the amount of contaminated water extracted through extraction wells, and to reduce the thicknesses of the floating hydrocarbon. Initial activities focused on the phreatic level, where the hydrocarbon thickness was measured from the extraction wells, using an oil/water interface probe. Later, a portable pumping system was installed

Figure 20.10: Aquifer restoration system, contaminated water is extracted and processed in a groundwater treatment plant and the recovered water is injected into the aquifer. **Source:** Results from the research by the authors.

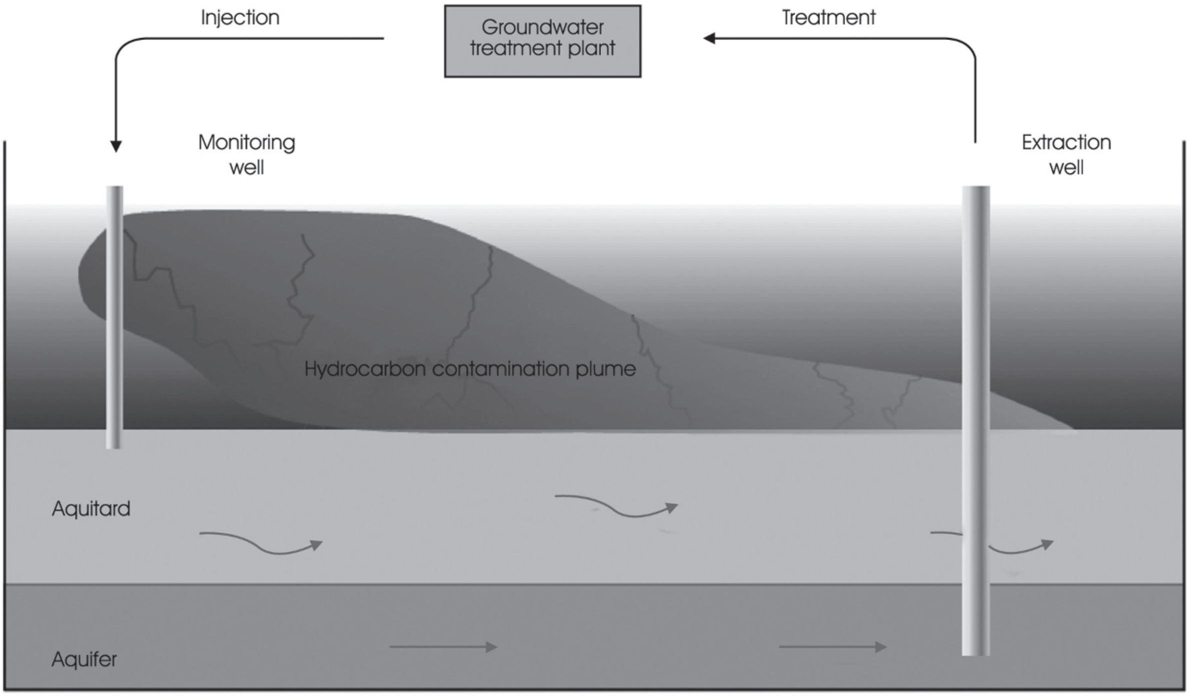
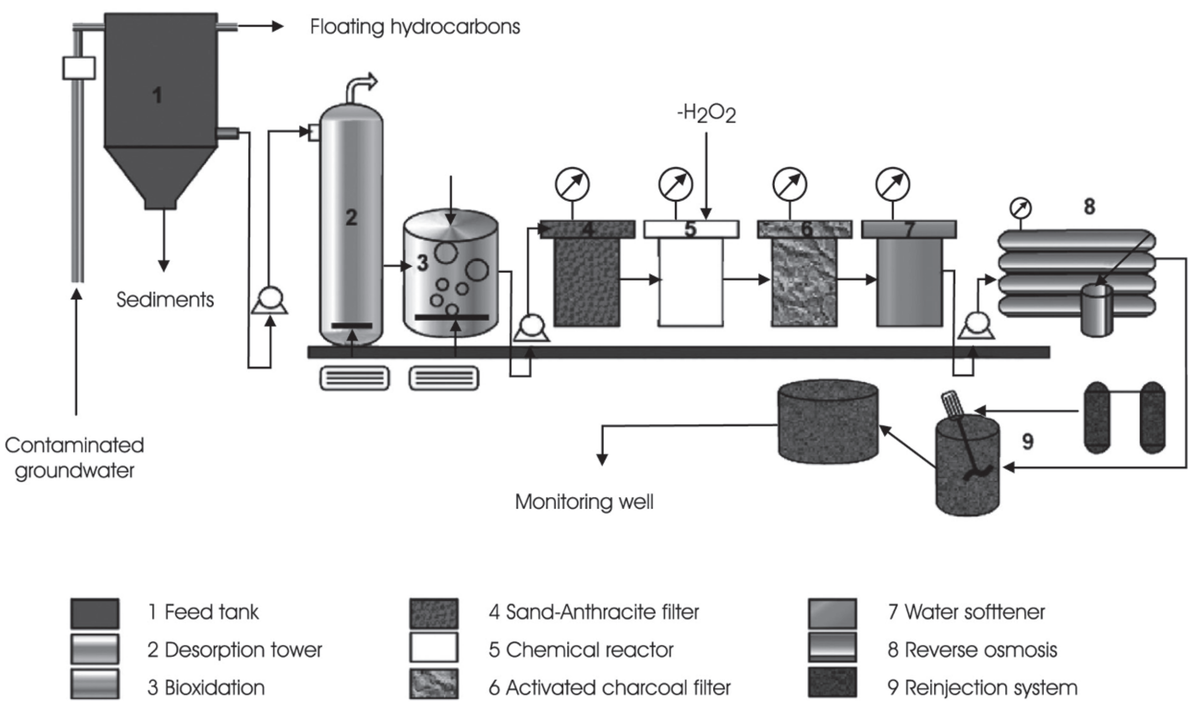


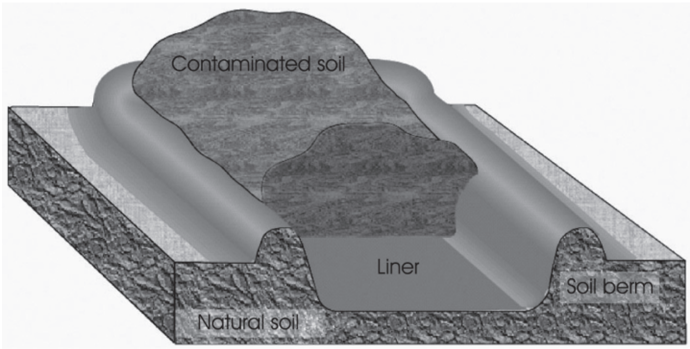
Figure 20.11: Design of the contaminated groundwater treatment plant. **Source:** Designed by the authors.



with an internal combustion power generator and a submersible electric pump to extract the hydrocarbon and the contaminated water.

With the daily pumping of the extraction wells the phreatic level was destabilized and became a drawdown zone, which generated a cone of depression in

Figure 20.12: A biotreatment cell that was constructed to deposit the soil contaminated with hydrocarbon, which includes a geo-membrane to remove the infiltration and contamination of the soil. Location of the existing wells in the study area. **Source:** Results from authors' research.



the aquifer that was big enough to trap the floating hydrocarbon and prevent its movement through the groundwater. After a period of three years, a total of 4,526.62 m^3 of contaminated water and floating hydrocarbon were extracted, recovering hydrocarbons of up to two mm during 24 hours, compared with the start of activities when up to 14 metres were recovered during the same time (figure 20.13).

20.10 Conclusions

With these studies, a hydrocarbon contamination plume was found that affected the soil, subsoil, and aquifer of the site. After the restoration technologies most appropriate to the site were selected and adopted, restoration was carried out.

1. Based on the results of this evaluation, the configuration of the contaminated hydrocarbon plume was established, combining three zones with particular characteristics of the soil and the local aquifer.
2. The highest permeability applied to the horizon of the first three metres of the soil, where a concentration of hydrocarbon storage occurred.
3. A low permeability zone was found below three metres and remained until cracks in the water table were located, which allowed the leaching of the hydrocarbon from the upper layer into the aquifer.
4. The water table oscillated between 15 and 20 metres, where the leaking hydrocarbon was located. In its floating phase it is up to 6 metres thick and in the dissolved form it is up to 1.5 metres thick.
5. The selected technologies for the restoration of the site are based on low permeability of the soil and on the hydrodynamic characteristics of the aquifer. For the first few metres of soil excavation the technology of bioremediation was applied and the restored soil was returned to its original place. The cleaning of the aquifer was achieved by extracting the hydrocarbon and treating the contaminated water in a *groundwater treatment plant* (GTP), but avoiding pollution is cheaper (CONAGUA, 2008).
6. With the remediation of 28,735.10 m^3 of contaminated soil and the extraction of 4,526.62 m^3 of contaminated water and floating hydrocarbon, the aquifer and the affected site were restored. Thus, the objective of the research project was fulfilled and the concentrations of hydrocarbon in the soil were reduced below the limits permitted by the standard NOM-138-SEMARNAT/SS-2003. Furthermore, the accumulation of hydrocarbon in the aquifer was reduced.

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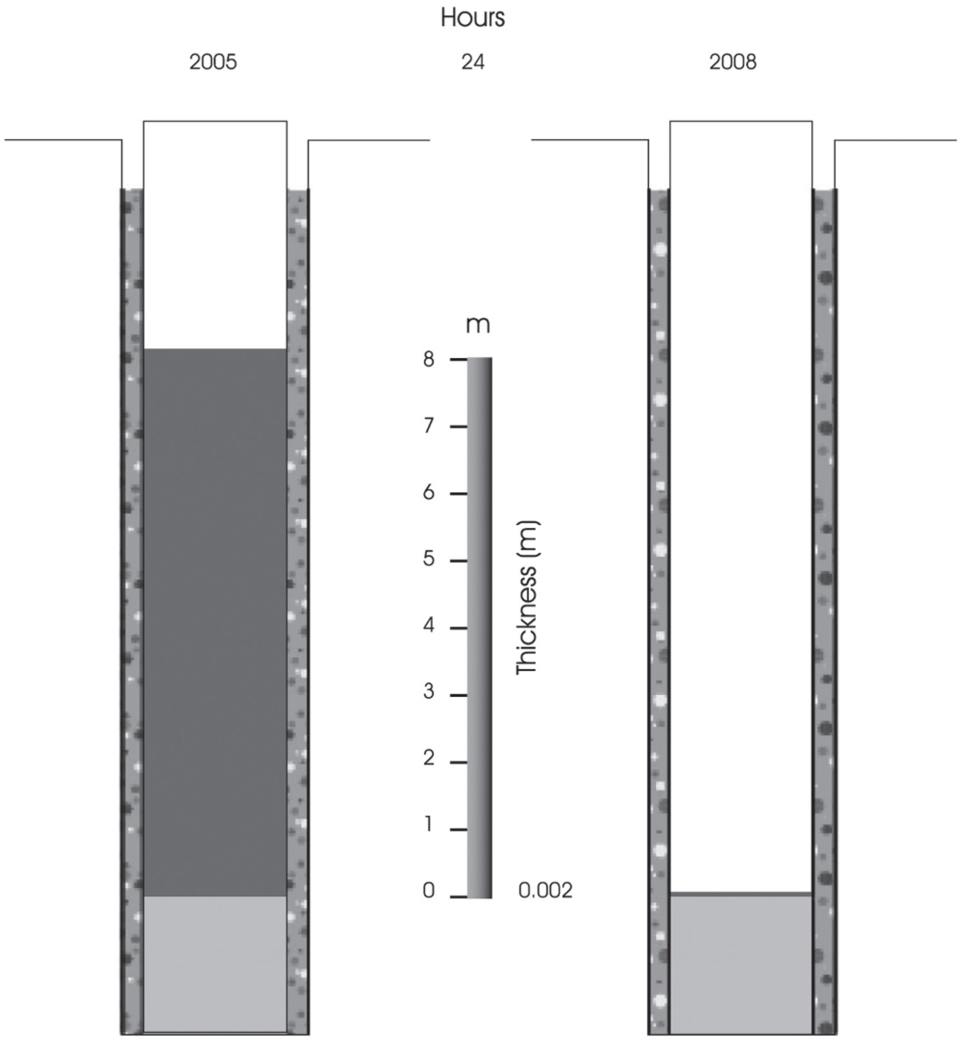
Figure 20.13: Recovery time for floating hydrocarbon thickness in groundwater at the beginning and end of the aquifer restoration. **Source:** Authors' research results.



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21 Endocrine Disrupting Compounds in Surface Water and Their Degradation by Advanced Oxidation Process with Ozone

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21.1 Introduction[1, 2]

This chapter presents the state-of-the-art techniques for identification and analysis of *endocrine disrupting compounds* (EDCs) and their degradation by *advanced oxidation processes* (AOPs). The document arises from a research project oriented towards developing a pilot-level technology for advanced oxidation using ozone for the degradation of EDCs present in surface water. Today EDCs are an environmental and public health problem. Their concentrations in water are very low (μg/l-ng/l), which complicates their identification and quantification. This analytical problem has given rise to the development of analytical methods that utilize such tools as *gas chromatography* (GC) and *liquid chromatography* (LC), coupled with *mass spectrometry* (MS). The most commonly used are GC/MS, GC/MS/MS in sequence, or LC-MS/MS. The use of the solid-phase extraction technique reduces the amount of time and the use of resources compared with conventional methods. The *advanced oxidation processes that use ozone* (AOP-O_3) are the most studied because of their high efficiency, greater than 80 per cent, in relatively short time periods – of the order of minutes. AOP-O_3 are capable of achieving partial or total (mineralization) oxidation of organic material. AOP-O_3 promise to be one of the most appropriate technological resources not only for treating surface water containing EDCs, including hormones and pharmaceuticals, but also for industrial effluents in general, contaminated with compounds of low biodegradability.

The *United States Environmental Protection Agency* (USEPA) has defined endocrine disrupting compounds (EDCs) as exogenous agents that interfere with the synthesis, secretion, transport, binding, action, or elimination of natural hormones responsible for maintaining homeostasis and reproduction in living beings (USEPA, 1997).

Anthropogenic activities, particularly industrial activities, generate and utilize a large range of EDCs, such as: alkylphenols, dioxins, bisphenol A, *polycyclic aromatic hydrocarbons* (PAHs), estyrene and phthalates. Numerous investigations have reported the effects of EDCs on the endocrine system of human beings such as: sexual differentiation, ovarian function, sperm production, and fertilization, including changes in thyroid hormones (Guzmán/Zambrano, 2007; Anway, 2006; Acosta et al., 2005; Daughton, 2005; Mitra et al., 2004; Ibarluzea et al., 2004; Sweeney, 2002; Rodger et al., 2000; Harrison et al., 1997).

'New' contaminants or '*emerging contaminants*' (ECs) also exist which represent a risk to humans and are not regulated by competent sanitary and environmental authorities. Today ECs are an object of study. This group of contaminants includes natural estrogens such as 17β-Estradiol, oestrone, oestriol; synthetic oestrogens such as 17α-Ethinylestradiol and mestranol, in addition to some pharmaceuticals, veterinary drugs, antiseptics, and beauty products. ECs are not necessarily endocrine disruptors, but their low biodegradability contributes to the disruption of the endocrine systems of living organisms, as in the case of diclofenac, diazepam, carbamazepine, and gemfibrozil, to name a few (USGS, 2008; Nakada et al., 2006; Snyder et al., 2005, 2006; Daughton, 2005; Petrovic et al., 2004; Ibarluzea et al., 2004; Schlumpf et al., 2004).

EDCs and ECs are dumped directly into the environment by various anthropogenic activities, and even though some industrial and domestic effluents are previously treated, these compounds persist and are

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2 Keywords: polycyclic aromatic hydrocarbons, endocrine disrupting compounds advanced oxidation processes, emerging contaminants

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found in effluents from *wastewater treatment plants* (WTP). As a consequence, these compounds have been identified in surface water (lakes, rivers, lagoon systems, etc.); by leaching, these compounds reach groundwater (Benotti et al., 2009; Ikehata et al., 2007; 2006; Bila et al., 2005; Kashiwada et al., 2002; Williams et al., 1999).

One problem in the detection techniques and analysis of EDCs in water is their low concentration (μg/l and ng/l), in addition to interference by other organic compounds, which means that more specific analytical methods need to be implemented. During the last decade *gas chromatography* (GC) and *liquid chromatography* (LC) methods, coupled with *mass spectrometry* (MS), have been developed; these are viable in time and resources and avoid complicated extraction techniques, sublimation of solvents, and liquid-liquid extractions (Liu et al., 2009; Gibson et al., 2007; Yu Zirui, 2007).

It has not been simple to degrade EDCs and ECs using conventional treatment processes, such as biological and physiochemical processes, because of their low biodegradability (Benotti et al., 2009; Kim et al., 2007; Nakada et al., 2006). Thus, *processes of advanced oxidation* (PAOs) arose as a necessary treatment. Studies are now available of the implementation of various PAOs at laboratory level for degrading EDCs and recalcitrant organic matter, or material of low biodegradability in general. The PAOs used until now seem to be the most viable because of the high efficiency (more than 80 per cent) obtained in relatively short times (of the order of minutes) for the degradation of EDCs and ECs.

This chapter presents the state-of-the-art techniques for the identification and analysis of endocrine-disrupting compounds present in surface water and their degradation by means of advanced oxidation processes using ozone.

21.2 Problems

21.2.1 Environmental and Public Health

A large number of studies at laboratory level have also reported the effects of EDCs and ECs on the endocrine systems of fish, reptiles, birds, and mammals (disruption of reproductive functions), such as: sexual differentiation, ovarian function, production of sperm, and fertilization (Guzmán/Zambrano, 2007; Anway, 2006; Acosta et al., 2005; Barceló, 2003; Lintelmann et al., 2003; Lister/Krack, 2001; USEPA, 1997).

There is evidence for anomalies and disturbances in the human endocrine system related to these substances, characterized by changes in the hormonal content in the thyroid and in the male and female reproductive systems, demonstrated by high incidences of breast cancer, prostate and testicular cancer, male infertility, and reduction in the production of sperm (Guzmán/Zambrano, 2007; Acosta et al., 2005; Mitra et al., 2004; Ibarluzea et al., 2004; Rodger et al., 2000; Harrison et al., 1997).

In the last decade, the effects of EDCs on living organisms have become more evident to the USEPA (2008, 2007), and in particular the Office of Investigation and Development has considered this theme as one of the six scientific research priorities in the United States. For this reason, there is increased interest, particularly in EDCs, among the international scientific community.

21.2.2 Water Treatment

A common characteristic of EDCs is the recalcitrance or persistence against natural or controlled biological degradation (Liu/Mizutani, 2009; Esplugas et al., 2007; Beltrán et al., 2008; Snyder et al.; 2006). In this context, water pollution from EDCs also represents a technical problem for treatment and purification of water, given that the conventional biological aerobic, anaerobic, coagulation-flocculation, filtration, and disinfection with chlorine treatments are not capable of removing or degrading the compounds (Benotti et al., 2009; Kim et al., 2007; Nakada et al., 2006; Snyder et al., 2005). In this regard, attempts have been made in recent years through research studies to establish a water treatment process for surface water contaminated with EDCs (Rivas et al., 2009; Sharma, 2008; Guedes et al., 2009; Esplugas et al., 2007; Coelho et al., 2007; Ikehata et al., 2007; Naghashkar/El-Din, 2005a; 2005b). Despite initial technical advances in this area, challenges still remain and alternatives need to be developed as part of the process of establishing a treatment that guarantees the elimination of EDCs in water so as to reduce the potential risk to public health.

EDCs and ECs are commonly found in domestic wastewater and in effluents from *municipal wastewater treatment plants* (MWTP) (Kim et al., 2007; Nakada et al., 2006), but mostly persist and are found in surface water in concentrations of mg/l^{-1} or ng/l^{-1}. Furthermore, surface water is the source of potable

Table 21.1: Occurrence of EDCs and ECs in surface water in different parts of the world. **Source**: Authors' research.

Compound	Concentration ($\mu g/l^{-1}$)	Location	Reference
	Pesticides		
2,4–D (2,4-Dichloro-pheno-xyacetic acid)	6.1 1.0-0.25 2-50 3-50	Clackamas River, Oregon, USA Tula City, Hidalgo, Mexico Chapala Lake, Mexico Sayula Lake, Mexico	Carpenter et al., 2008 Gibson et al., 2007 Álvarez, 2007
Dieldrin	<0.080	USA	Barnes et al., 2002
Endrin	$19x10^{-6}$ nr	South Fork Shenandoah River, Virginia, USA Chapala Lake, Mexico	Álvarez et al., 2008 Álvarez, 2007
Lindane	<0.050 $240x10^{-6}$	USA South Fork Shenandoah River, Virginia, USA	Barnes et al., 2002 Álvarez et al., 2008
Malathion	0.027	Mobile River, USA	McPherson et al., 2003
Methyl parathion	<0.0060	USA	Barnes et al., 2002
Methoxychlor	$47\ x10^{-6}$ nr	South Fork Shenandoah River, Virginia, USA Chapala Lake, Mexico	Álvarez et al., 2008 Álvarez, 2007
	Various Compounds		
4-Methylphenol	<0.060	USA	Barnes et al. (2002)
4-Nonylphenol	<0.5 <0.1-0.15 <0.01-0.49 <0.01-0.92 0.11-0.64 0.02-0.3	USA Catalonia, Spain Baden-Württemberg, Germany Greats Lakes, USA and Canada USA Japan	Barnes et al. (2002) Petrovic et al. (2002) Bolz et al. (2001) Bennett and Metcalfe (1998), Bennie et al., 1997 Naylor et al., 1992 Tsuda et al., 2002
4-Nonylphenol monoethoxylate	<1.0	USA	Barnes et al., 2002
4-Nonylphenol diethoxy-late	<1.1	USA	Barnes et al., 2002
Phenol	<0.25	USA	Barnes et al., 2002
Nonylphenol ethoxylate	<0.1-31 <0.02-7.8 <0.06-0.60 <0.04-0.42	Catalonia, Spain Great Lakes, USA and Canada USA Japan	Petrovic et al., 2002 Bennett and Metcalfe, 1998 Bennie et al., 1997 Naylor et al., 1992 Tsuda et al., 2002
Octylphenol	<0.01-0.19 <0.005-0.084 <0.02-0-09	Baden-Württemberg, Germany Great Lakes, USA and Canada Japan	Bolz et al., 2001 Bennett/Metcalfe, 1998 Bennie et al., 1997 Tsuda et al., 2002
	Antibiotics		
Sulphamethizole	<0.10	USA	Barnes et al., 2002

Compound	Concentration (μg/l^{-1})	Location	Reference
Sulfamethoxazole	<0.10 3.7x10^{-3}	USA Maury River, Virginia, USA	Barnes et al., 2002 Álvarez et al., 2008
Sulphathiazole	<0.10	USA	Barnes et al., 2002
Tetracycline	<0.05	USA	Barnes et al., 2002
Triclosan	0.23	USA	Barnes et al., 2002
Trimethoprim	<0.014 65x10^{-3}	USA South Fork Shenandoah River, Virginia, USA	Barnes et al., 2002 Álvarez et al., 2008
Pharmaceuticals			
Acetaminophen	0.016 <0.036	USA Platte River, Nebraska, USA	Barnes et al., 2002 Vogel et al., 2005
Acetylsalicylic acid	1	Germany	Ternes, 1998
Diclofenac	1	Germany	Ternes, 1998
Gemfibrozil	<0.015	USA	Barnes et al., 2002
Ibuprofen	<0.018 1 0.8-2.2x10^{-3}	USA Germany Tula City, Hidalgo, Mexico	Barnes et al., 2002 Ternes, 1998 Gibson et al., 2007
Naproxen	0.05-0.4 0.8-0.9x10^{-3}	Germany Tula, Hidalgo, Mexico	Ternes et al., 1998 Gibson et al., 2007
Ranitidine	<0.01 <0.013	USA River Platte, Nebraska, USA	Barnes et al., 2002 Vogel et al., 2005
Salicylic acid	7.8-9.6x10^{-3}	Tula City, Hidalgo, Mexico	Gibson et al., 2007
Steroids			
17-Ethinylestradiol	8.1x10^{-3} 0.06x10^{-3}	South Fork Shenandoah River, Virginia, USA Tula, Hidalgo, Mexico	Álvarez et al., 2008 Gibson et al., 2007
17-Estradiol	<0.5 2.3x10^{-3} 0.01-0.02x10^{-3}	USA Shenandoah River, Virginia, USA Tula, Hidalgo, Mexico	Barnes et al., 2002 Álvarez et al., 2008 Gibson et al., 2007
Oestriol	3.4x10^{-3}	River Fork Shenandoah Sur, Virginia, USA	Álvarez et al., 2008
Oestrone	1.6x10^{-3} 0.16-0.17x10^{-3}	Rio Fork Shenandoah Sur, Virginia, USA Tula, Hidalgo, Mexico	Álvarez et al., 2008 Gibson et al., 2007

water supplies, thereby putting the population that consumes this water at risk (Benotti et al., 2009; Sharma, 2008; Kim et al., 2007; Gibson et al., 2007). Table 21.1 gives a summary of the presence of EDCs and ECs in water and soil in different parts of the world, including some of the principal water sources in Mexico. The principal sources of this information are technical reports written by the U.S. Geological Survey (USGS, 2002, 2008) and by Petrovic et al. (2004).

Of the compounds presented in table 21.1, the following have been declared endocrine disruptors: pesticides: 2,4-D (2,4-dichlorophenoxyacetic acid), endrin, lindane, and methoxychlor (USEPA, 2000, 1997); steroids: 17β-Estradiol and 17α-Ethinylestradiol (Brion et al., 2004; Lange et al., 2001). The effects of disruption of antibiotics and other pharmaceuticals are currently under study (Nakada et al., 2006; Snyder et al., 2006, 2005; Daughton, 2005; Petrovic et al., 2004; Ibarluzea et al., 2004).

21.3 Analysis of Identification of EDCs and ECs Present in Surface Water

In general, the identification and quantification of EDCs and ECs includes sampling, chromatographic separation, and final detection (Gibson et al., 2007; Yu Zirui, 2007; Kolpin et al., 2002).

The techniques utilized are of different levels of complexity, sensitivity, reliability, and cost. Due to the low concentrations of the majority of the EDCs found in water, the extraction procedures generally applied are for concentrations of compounds of interest in an aqueous matrix. Different types of analytical instrumentation can be used for measuring the compounds of interest in the extracts. However, MS or MS in tandem with GC or LC have become the most commonly used instrumentation for the analysis of these traces compounds.

The technique LC-MS/MS has shown to be a versatile technique that is applicable for the majority of polar or thermolabile EDCs (e.g. antibiotics). However, the LC-MS/MS method is relatively expensive. In comparison with LC, the analysis of EDCs by GC/MS, although more limited in scope, offers a useful and sensitive method for the determination of EDCs and is more affordable for the majority of laboratories. However, often the samples require additional derivatization steps following extraction to obtain the less polar and/or more volatile target compounds. The general steps in the analysis of EDCs by GC/MS are: collecting the sample, extraction, derivatization, and finally, the identification and quantification of the compounds (Liu et al., 2009; Flemming/Bent, 2003; Kolpin, et al., 2002).

The processes of extraction, sublimation of the solvent, steam distillation, and liquid-liquid extraction methods have been replaced by other more efficient and versatile methods such as *solid-phase extraction* (SPE) and solid-phase microextraction techniques. SPE frequently uses discs and disposable cartridges. In the analysis of EDCs, octadecyl (C18) bonded silica cartridges have been widely used for extraction (Kelly et al., 2000; Jeannot et al., 2002; Mouatassim-Souali et al., 2003, Guedes et al., 2009).

Table 21.2 presents a compilation of the analysis methods used by various authors for the identification of EDCs and ECs.

21.4 Advanced Oxidation Processes for degrading EDCs

In response to the limited availability of technology for treating surface water contaminated with EDCs in the process of purification, current research is aimed at developing treatment processes to degrade these types of contaminants and to reach high efficiencies in their degradation. Some of these processes are known as AOPs, with its originality based on the coupling of two or more oxidizing agents (O_3/pH↑, O_3,/H_2O_2, Fe^{2+}/H_2O_2, O_3/Cat, H_2O_2/UV, O_3/UV) in order to generate hydroxyl radicals ($OH^{\bullet}$), the principal species that cause rapid and complete oxidation of recalcitrant or difficult-to-biodegrade compounds, including EDCs (Rivas et al., 2009; Sharma et al., 2008; Guedes et al., 2009; Esplugas et al., 2007; Coelho et al., 2007; Ikehata et al., 2007; Naghashkar/El-Din, 2005a; 2005b; López-López et al., 2007, 2004; Beltrán, 2004). In particular, this document presents the state of research concerning advanced oxidation processes based on ozone for degrading EDCs present in water, in the process of developing and validating a technology at a pilot level. Below is a brief description of the scientific fundamentals of POA-O_3, not including the processes that utilize ultraviolet radiation.

Process O_3/pH↑

The action of ozone on organic material in aqueous media has been thoroughly studied; it has been concluded that the oxidation reaction occurs by molecular or radical routes. The molecular route acts selectively on organic compounds that have double bonds and are prevalent at low pHs. For the radical route, the principal oxidizing agent is the radical $OH^{\bullet}$ that acts in a non-selective form on organic compounds (Guedes et al., 2009; Beltrán et al., 2008, Beltrán, 2004; López-López et al, 2004; Hoigné/Bader, 1976).

The O_3 molecule and the HO^{o} radical have the potential for oxidation-reduction (E^{o}) of 2.8 and 2.07 volts, respectively; fluorine has a more elevated potential (3.0), and these are the three oxidant species with the highest potentials.

On the other hand, the action mechanisms of ozone on organic material present in water, by molecular and radical routes, show great differences in the magnitudes and velocities of reactions, the latter showing a function directly proportional to their respective constants, $k_{O3/M}$ y $k_{HO^{\bullet}/M}$. Table 21.3 shows a comparison of the rate constants of ozone oxida-

Table 21.2: Methods of analysis used by various authors for the identification of EDCs and ECs. **Source:** Adapted from Yu Zirui (2007).

Compound	Sample preparation (extraction, elution, sample volume)	Derivatization	Internal standard/surrogate standard	LOD and LOQ (ng/l), matrix	Detection	Reference
Steroids						
E1, E2, 17-oestradiol, EE2	SDB-XC disc; methanol; 1 litre sample	Dimethyldichlorosilane (SILA) in toluene	PCB 103	LOD: 0.1-0.6 in surface water	CG/EM-EM	Belfroid et al., 1999
E1, E2, EE2	C_{18} disc; methanol-water; 2.5 l sample	MTBSTA containing 1% TBDMCS in acetonitrile	Deuterated analytes	N/A	CG/EM and CG/EM-EM	Kelly, 2000
E1, E2, E3, EE2	Silica cartridge C_{18}; acetonitrile in water; 200 ml sample	N/A	N/A	LOD: 10-15, in wastewater	CL-UV	Alda and Barcelo, 2001
E1, E2, EE2, NP, 4-OP	LiChrolut EN; acetone and metanol; 1 litre sample	Pentafluorobenzyl chloride (PFBCl)	1,4-Bispentafluorobenzyl benzene (BPFBB) as internal standard	LOD: 0.05-0.1 in surface water	HRGC/NCI-EM and CG-ECD	Kuch and Ballschmitter, 2001
E1, E2, EE2	LL extraction with CH_2Cl_2 at ambient pH	Trimethylsilyl (TMS)	E2-d_4 y cholesterol-d_4	N/A	CG/EM	Kolpin et al., 2002
E1, E2, E3, EE2 and their conjugates	Speeddisk-C18; water/acetone (4:1) and acetate; 2 l sample	50 l Pentafluoropropio-nic acid anhydride (PFPA)	N/A	LOQ: 0.04-0.32 , in wastewater	CG-EM	Mouatassim-Souali et al., 2003
E1, E2, E3 and EE2, NP, OP	N/A	anhydrides HFBA and TFAA in toluene	N/A	NR	CG/NCI-EM	Lerch and Zinn, 2003
E1, E2,E3,EE2, Moestranol	Oasis C18 cartridge; ethylacetate	MSTFA in ethylacetate	Deuterated E2	LOQ: 3-5 in surface water	CG/EM or CG/EM-EM	Quintana *et al.*, 2004
E3, E2, EE2,E1, DES	HLB Oasis cartridge, MTBE 3 ml, wastewater 50 ml sample	N/A	17-Oestradiol-17- acetate as internal standard	LOD (ESI):4-15; (APPI): 6-16 LOQ (ESI):10-60; (APPI):20-50; surface water and groundwater	CL-EM-EM with ESI/APPI	Hsing-Chang et al., 2009
Various compounds						
4-t-OP, 4-NP, BPA	C18 and polyestyrene copolymer ENV+; acetone; 1L sample	phenyltrimethylammonium-oxide	Biphenyl	LOQ: 4-to 0.02-0.05 MilliQ water	CG-EM	Bolz et al., 2000
4-n-NP, 4-n-OP, BPA	SPME	BSTFA	N/A	LOD: 10-100 MilliQ water	CG-EM	Helaleh et al., 2001
Various compounds						
NP, NP1EO, NP2EO, NP1EC, NP2EC	SPME	Dimethyl sulphate (DMS)	n-nonyoxylbenzoic methyl ester	LOD: 20-1500 MilliQ water	CG-EM	Díaz and Ventura, 2002

Compound	Sample preparation (extraction, elution, sample volume)	Derivatization	Internal standard/surrogate standard	LOD and LOQ (ng/l), matrix	Detection	Reference
4-NP, 4-t-OP, BPA, E1, E2, E3, EE2	C_{18} cartridge; hexane-dichloromethane (90:10), methanol-dichloromethane (90:10); Oasis HLB; methanol-diethylether (10:90); 1 litre sample	BSTFA	BPA-d_{16}	LOQ (HLB extraction): 2-10 in MilliQ water	CG-EM	Jeannot, 2002
NP, NP1EO, NP2EO	LL extraction, pentane	N/A	$^{13}C_6$-NPnEO	LOD: 4-2122 in wastewater	HRGC/EM	Planas et al., 2002
t-NP, BPA, EE2	SPME	N/A	4n-NP, _-oestradioldiacetate and [$^2H_{14}$]BPA	LOQ: 120-3000 in wastewater	CG-EM	Braun et al., 2003
NP, NP1EO, NP2EO,NP3EO, NP1EC, NP2EC	Bond Elut C18-HF cartridge; methylacetate	N,O-bis(trimethysilyl) acetamide (BSA) in methyl acetate	OP-d, OP1EO-d, and OP1ECd as surrogates; phenanthrene-d_{10} and pyrened$_{10}$ as internal standards	LOD: 2.5-9.5 in MilliQ water	CG/EM-EM	Hoai et al., 2003
4-n-NP, NP1EO, NP2EO,BPA, TCS	C-18, poly(divinylbenzene-co-N-vinylpyrrolidone), styrene-divinylbenzene hydroxylated estyrene-divinylbenzene; dichloromethane-hexano (4:1); 100 mL sample	BSTFA and pyridine	BPA-d_{16}	LOD: 30-410 in wastewater	CG-EM	Gatidou et al., 2007
Pharmaceuticals						
Carbamazepine, ibuprofen, diclofenac, ketoprofen, naproxen, clofibric acid, bezafibrate, gemfibrozil, diazepam	RP-C_{18} cartridge; 4ml acetone; 1 litre sample	PFBBr in cyclohexane with triethylamine at 100 ºC for 2h	2,3-dichlorophenoxya-cetic (2,3-D) as surrogate standard	LOQ: 13-32 in groundwater	CG/EM	Sacher, 2001
Carbamazepine, ibuprofen, diclofenac, ketoprofen, naproxen, clofibric acid	Oasis HLB; ethyl acetate - acetone (50/50); 1 litre sample	Diazomethane	[$^{13}C_6$]metolachor, atrazine-d_3, MCPA-d_3, dimethenamide-d_3, Mecoprop-d_3, dihydrocarbamazepine	LOD: 0.3-4.5 in surface water	CG-EM	Öllers., 2001
21 prescription and non-prescription drugs	Oasis HLB; CH_3OH and mixture of CH_3OH and $C_2HCl_3O_2$	N/A	C_{13}-phenacetin as surrogate standard	NR	HPLC	Kolpin et al., 2002
Nine acidic pharmaceuticals	LiChrolut 100 RP-18; methanol; 500 ml sample	N/A	N/A	LOD: 5 – 20 in STP effluent	CL-tandem EM	Miao et al., 2002

Compound	Sample preparation (extraction, elution, sample volume)	Derivatization	Internal standard/surrogate standard	LOD and LOQ (ng/l), matrix	Detection	Reference
Naproxen, ibuprofen, E1,E2, BPA, clorophene, triclosan, fluoxetine, clofibric acid, acetaminophen	SDB-XC Empore disk; methanol, dichloromethane and methane	BSTFA	Phenanthrene-d_{10} as internal standard; acetaminophen-d4, BPA-d16, and E1-d4 as surrogate standard	LOD: 0.1-25.8 in surface water	CG-EM	Boyd et al., 2003
Diclofenac, ibuprofen, clofibric acid, phenazone, propyphenazone	C_{18} cartridge; 2.5ml methanol; 1l sample	200 l PFBBr and 5 l trimethyamine in toluene, 110 ºC, 1h	3,4-D as surrogate standard; 2,4-dichlorobenzoic acid as internal standard	LOQ: 1.6-60 in wastewater	GC/ITD-MS	Koutsouba et al., 2003
Ibuprofen, naproxen, ketoprofen, tolfenamic acid, diclofenac	Oasis HLB cartridge; ethyl acetate; 500 ml samples	MTBSTFA	Meclofenamic acid as surrogate standard PCB-30 as internal standard	LOQ: 20-50 in surface water	CG-EM	Rodríguez, 2003
Carbamazepine, clofibric acid, diclofenac, ibuprofen, ketoprofen, naproxen	Waters oasis HLB; 1l Sample	Diazomethane	Mecoprop-d3, dihydrocarbamazepine	NR	CG-EM	Tixier, 2003
21 endocrine disrupting phenols and acidic PhACs	Oasis MAX SPE; methanol and formic acid in methanol (2:98)	EDCs by Pentafluoropropio-nic acid anhydride (PFPA); acidic PhACs by MTBSTFA	Deuterated E2, BPA for EDCs; 2,3-D for acidic drugs	LOD: 10-100 in wastewater	CG-EM	Lee et al., 2005
Caffeine, carbamazepine, diclofenac, ibuprofen, ketoprofen, naproxen,	Oasis HLB cartridges, methanol, acetonitrile and 50 mM KH_2PO_4 solution	N/A	N/A	LOQ: 6.2-319.8 and 3.0-160	HPLC-DAD	Santos et al., 2005
51 EDCs and PhACs	Oasis HLB; methanol and methanol/MTBE (10:90), and DCM	N/A	Related deuterated compounds	LOD: 1-10 in surface water	CG-EM/EM; CL-ES/EM	Trenholm et al. 2006
Clofibric acid, ibuprofen, carbamazepine, naproxen, ketoprofen, diclofenac	Oasis HLB; methanol	Tetrabutylammo-nium hydrogen sulphate ($TBAHSO_4$)	Deuterated chrysene	LOD: 1.0-8.0 in drinking water	CG-EM	Lin et al., 2005

Compound	Sample preparation (extraction, elution, sample volume)	Derivatization	Internal standard/surrogate standard	LOD and LOQ (ng/l), matrix	Detection	Reference
Ibuprofen, naproxen	Sodium dodecyl sulphate dodecil (SDS) hemimicelles formed onto orto-γ-alúmina, 0.3 M NaOH:methanol solution (70:30 v/v), 0.75 a 1 litre samples.	N/A	Ibuprofen and naproxen analytical grade	NR	CL/UV	Costi et al. 2008

N/A: not applicable; NR: not reported
APPI: atmospheric pressure photoionization
BPA: biphenil A
CL-UV: Liquid Chromatography-UV Detector
DAD: diode array detection
DES: Diethylboestrol
DMC: Dimethylcarbonate
E3: Oestriol
ECD: Electron Capture Detector
EI: Electronic Impact
E1: Oestrona
E2: 17β-oestradiol
EE2: 17α- Ethinyloestradiol
ESI: Electrospray Ionization
HRGC: High-Resolution Gas Chromatography
HFBA: Heptafluorobutyric Acid chromatography
HPLC: High performance liquid
ITD: Ion Trap Detector
LL: liquid-liquid (extraction)
LOD: limit of detection
LOQ: límits of quantification
MBTFA: N-Methyl-bis (trifluoroacetamide
MTBSTFA: *N*-Methyl-*N*-[tert-butyldimethyl-silyl]trifluoroacetimide
NCI: negative ion chemical ionization
NP: 4-Nonylphenol
NP1EC: 4-nonylphenoxy acetic acid
NP2EC: nonylphenoxy ethoxy acetic acid
NP1EO: nonylphenol monoethoxylate
NP2EO: nonylphenol diethoxylate
NP3EO: nonylphenol triethoxylate
PFBBr: Pentafluorobenzyl bromide
SDB: Styrene-divinylbenzene
TBDMCS: Tert-butyl dimethylchlorosilane
TFAA: Trifluoroacetic anhydride
t-NP: ternonylphenol
4-n-NP: 4-n-nonylphenol
4-n-OP:4-n-octylphenol

tion on some EDCs and pharmaceuticals (Rosal et al., 2008, Naghashkar/El-Din, 2005a).

The difference between magnitudes of the kinetic constants is caused by the action of the $OH^{\bullet}$ radicals originated during the decomposition of ozone. From this stems the importance of developing an AOP-O_3 and establishing the conditions under which the two-phase reactor (gas-liquid) must operate with the objective of achieving maximum efficiency in the production of $OH^{\bullet}$ radicals and consequently the degrading of EDCs.

Some studies that used AOP-O3 at different pHs and doses of oxidant to degrade different EDCs are presented in Table 21.4.

Process O_3/H_2O_2

Different studies have used AOPs, particularly the O_3/H_2O_2 system, to degrade EDCs (Guedes et al., 2008; Ikehata et al., 2006; Naghashkar/El-Din, 2005a, 2005b; Zwiener/Frimmel 2000; Beltrán, 2004, 1999; Balcioglu/Otker, 2003). During the application of the O_3/H_2O_2 system, hydrogen peroxide (H_2O_2) hydrolyzes in the following manner:

$$H_2O_2 + H_2O \leftrightarrow HO_2^- + H_3O^+ \quad (1)$$

Table 21.3: Comparison of rate constants of molecular ($k_{O3/M}$) and radical ($k_{HO\bullet/M}$) oxidation of O_3 on some EDCs and pharmaceuticals. **Source:** Adapted from Naghashkar and El-Din (2005a)

Substances	$k_{O3/M}$ ($l.mol^{-1}.s^{-1}$)	$k_{HO\bullet/M}$ ($l.mol^{-1}.s^{-1}$)
Pentachlorophenol (phenol-chloride)	$> 10^5$	$4x10^9$
Atrazine (pesticide)	2.25-6	$(2.4-2.7)x10^9$
Endrin (pesticide)	<0.02	$1.1x10^9$
17α-ethinyloestradiol (ovulation inhibitor)	$7x10^5$	$1.08x10^{10}$
Diazepam (tranquilizer)	0.75	$7.2x10^5$
Bezafibrate (lipid regulator)	$5.9x10^2$	$7.4x10^9$
Carbamazepine (anti-epileptic/analgesic)	$7.81x10^4$	$2.05x10^9$
Paracetamol (analgesic)	$4.29x10^4$	$2.2x10^9$

The mechanism for generation of $OH^{\bullet}$ radicals starts with a very rapid attack of ozone on the hydroperoxide anion (HO_2^-) which originates from the decomposition of H_2O_2 (Beltrán, 2004):

$$HO_2^- + O_3 \rightarrow OH^{\bullet} + O_2^{\bullet -} + O_2 \quad (2)$$

Guedes et al. (2008), Ikehata et al. (2006), and Naghashkar and El-Din (2005a, 2005b) have shown the effectiveness of AOPs for degrading a great variety of EDCs (natural and synthetic hormones and pharmaceuticals) at a laboratory level, highlighting the advantages of coupling O_3/H_2O_2 as a simple, effective, and economical process with respect to other AOPs.

Despite the results obtained from this O_3/H_2O_2 process, technical questions arise from the investigation of the problematic gas-liquid transfer (ozone/water) in a continuous or semi-continuous treatment system. It is necessary to estimate the $OH^{\bullet}$ free radicals that take place in the oxidation process of the compound of interest and the $OH^{\bullet}$ that terminate participating in secondary reactions or sub-products, with the objective of establishing global models that represent the oxidation process of EDCs.

Process O_3/Cat: This O_3/Cat [Cat=Co(II) Fe(II), Mn(II) Ti(II)] type of AOP, also called catalytic ozonization, is investigated for the production of $OH^{\bullet}$ radicals to degrade EDCs and, in general, recalcitrant contaminants such as pesticides, dyes, and chlorinated compounds (Sharma, 2008; Ikehata et al., 2007; Beltrán, 2004; Rivas et al., 2003; Cortés et al., 2000; Gracia et al., 2000). In this sense, Rivas et al. (2003) have shown that the decomposition of ozone in the presence of Co(II) follows a pseudo-first-order kinetic with respect to ozone. These authors have also established that the generation of $HO^{\bullet}$ radicals from the catalyzation of O_3 by Co(II) occurs in an acidic medium; this mechanism is represented by equation 3. However, this mechanism can be inhibited by alkaline media. This phenomenon is attributed to the fact that $Co(OH)_2$ at pH>8 is less soluble, which can lead to the precipitation of the latter, causing diminished catalysing power of Co(II).

$$+ Co^{++} + H_2O \rightarrow Co(OH)^+ + O_2 + H \quad (3)$$

Cortés et al. (2000) successfully applied the O_3/Cat AOP, at a laboratory level and in a discontinuous regime, to degrade organochlorine compounds at concentrations of $6x10^{-5}$ M; utilizing Fe(II) and Mn(II) as catalysts at concentrations of $6x10^{-5}$ M. In the first stage, the O_3/Fe(II) and O_3/Mn(II) AOPs were applied to prepared solutions with chlorinated compounds; in a second stage this AOP was applied to industrial water also containing chlorinated compounds. The results of the first stage showed an oxidation efficiency of these compounds of the order of 98 and 100 per cent. In the second stage, Cortés et al. (2000) established that the degradation velocity of the chlorinated compounds is a function inversely proportional to the number of Cl^{-1} ions present in the compound, given that chlorobenzene was more rapidly oxidized than di-, tri-, tetra- and pentachlorobenzene. This also shows that the chemical stability and the recalcitrance of the compound are due to the number of chlorines present in the organic chemical species.

Ikehata et al. (2007) and Beltrán (2004) have applied O_3/Cat AOPs to sources of drinking water supply, showing degradation of EDCs of more than 80 per cent, in relatively short times, following a first-order kinetic in the presence of Co(II) and Mn(II). Also, these authors have shown that the $HO^{\bullet}$ radicals, generated during the destruction of O_3, play an important role in the oxidation of EDCs.

Table 21.4 presents a compilation of AOP-O_3 as described above. The references are listed in chronological order from the beginning of the present decade, without considering the type of EDCs or recalcitrant compound,

According to the information in table 21.4, ozonization is the AOP most used for the removal of EDCs and ECs. Approximately 90 per cent of AOPs encountered in the literature corresponds to ozonization, ozonization with H_2O_2 and ozonization with a catalyst. The removal of EDCs and ECs was achieved using doses of ozone of 0.1 to 30 mg/l. Removal of approximately 90 per cent was achieved for the following EDCs: pesticides, anti-inflammatories, anti-epileptics, antibiotics, and natural and artificial oestrogens. However, some substances are more recalcitrant to oxidation with ozone, such as *clofibric acid* and X-ray contrast media agents.

21.5 Conclusions

The EDCs are a group of compounds which are potentially dangerous for the endocrine system of living beings, found in the environment, particularly in surface water, in very low concentrations, complicating their identification. Another group, the ECs, which includes steroids (natural and synthetic), pharmaceuticals, veterinary drugs, antiseptics, and beauty products is also found in water. Both EDCs and ECs affect water quality and potentially impact sources of drinking water, ecosystems, and human health. The

Table 21.4: AOP-O_3 applied to different types of water and under different conditions. **Source:** Adapted from Esplugas et al. (2007).

Compound	Type of water	Treatment	Operation Conditions	Results and Commentaries	Reference
Clofibric acid, ibuprofen and diclofenac	Distilled and drinking water	O_3/H_2O_2 molar ratio (O_3/ H_2O_2) = 2:1:1	C_{O3}= 1.0 mgl^{-1}; Tr = 10 min; C_0 = 2 μgl^{-1}, distilled water C_{O3} = 1.0 mgl^{-1}; Tr = 10 min; C_0 = 2 μl^{-1}, distilled water C_{O3} = 1.0 mgl^{-1}; Tr = 10 min; C_0 = 2 μgl^{-1}, drinking water C_{O3} = 3.7 mgl^{-1}; Tr = 10 min; C_0 = 2 μgl^{-1}, drinking water C_{O3} = 5.0 mgl^{-1}; Tr = 10 min; C_0 = 2 μgl^{-1}, drinking water	8% of clofibric acid, 12% of ibuprofen and 97% of diclorfenac were removed 50% of clofibric acid, 50% of ibuprofen and 100% of diclorfenac were removed 10% of clofibric acid, 30% of ibuprofen and 100% of diclorfenac were removed 90% of clofibric acid, 90% of ibuprofen and 100% of diclorfenac were removed 97.9% of clofibric acid, 99.4% of ibuprofen and 100% of diclorfenac were removed	Zwiener and Frimmel, 2000
Carbamazepine	Aqueous solution	Ozonization	Ratio O_3/CBZ = 10; C_0 = 0.8 mg l^{-1}; C_{O3} = 1.0 mg l^{-1}; Tr = 10 min Tr = 10 min Ratio O_3/CBZ = 10; C_0 = 118 mg l^{-1}; Tr = 10–60 min	Complete removal of carbamazepine in natural water was reached. After 60 min of treatment a little TOC removal was observed	Andreozzi et al., 2002
Carbamazepine, benzafibrate, diclofenac and clofibric acid	Distilled and drinking water	Ozonization	C_0 =1 μgl^{-1}; C_{O3} = 0.5 3.0 mg l^{-1}; Tr=20 min	97% of carbamazepine and diclofenac were eliminated with ozone dose of 0.5 mg l^{-1}. Bezafibrate was 50% removed with ozone dose of 1.0–1.5 mg l^{-1} and 90% was removed with ozone dose 3.0 mg l^{-1}. Only 10–15% removal of clofibric acid with 0.5 mg l^{-1} ozone dose. At higher ozone dose (2.5–3.0 mg l^{-1}) 40% of chlofibric acid was removed	Ternes et al.,2003
Paracetamol	Aqueous solution	Ozonization	pH 2.0 and 7.0; C_0 = 5.0 mmol l^{-1}; *T*=25 C	Complete removal of paracetamol with 30% mineralization. Oxalic, glioxalic, cetomalonic and formic acids and hydroquinone were identified as intermediates	Andreozzi et al., 2003
Clofibric acid	Aqueous solution	Ozonization	Tr = 60 min; pH 2.0–6.0; C_0 = 1.0–1.5 mmol l^{-1}; C_{O3} aqueous = 1.0×105 mol l^{-1}	100% removal of clofibric acid was reached in 20 min with 34% mineralization. 49% mineralization was reached in 60 min. No halogen compounds were detected in the oxidation product	Andreozzi et al., 2003

Compound	Type of water	Treatment	Operation Conditions	Results and Commentaries	Reference
Bezafibrate, carbamazepine, diazepan, diclofenac, 17α-Ethinyloestradiol, ibuprofen, iopromide, sulfametoxazol and roxithromycin	Milli Q, river and lake water	Ozonization	C_{O3} = 0.1; 0.2; 0.5; 1.0 and 2.0 mgl^{-1}; C_0 = 0.5 μmol l^{-1}; natural water properties: pH 7.2–7.9; COD= 0.8–3.7 mg l^{-1}; alkalinity = 0.7–5.8 mol l^{-1} HCO^3	Ozone doses ranging from 0.2 up 0.5 mg l^{-1} were observed with 97% removal of all compounds. Removal of bezafibrate was lower	Huber et al., 2003
Iodinated X-ray contrast media, antibiotics, beta blockers, antiphlogistics, lipid regulator metabolites, antiepileptics and oestrogens	DWTP effluent	Ozonization	C_{O3} = 5, 10, 15 mg l^{-1}; effluent properties: pH 7.2; DOC=23 mgl^{-1}; COD=30 mgl^{-1}; SST = 4.5 mg l^{-1}	Ozone doses ranging from 5 up to 15mg l^{-1} were necessary for complete removal of these compounds	Ternes et al., 2003
Oestrogens (17β-Estradiol and 17α-Ethinyloestradiol) and bisphenol	Distilled water	Ozonization	*C*0 = 100 nmol l^{-1}; *T*=20 C; contact time = 1–120 min; *C*O3 = 1.5 mgl^{-1}	100% removal of bisphenol A, 17β-Estradiol and 17α-Ethinyloestradiol. A reduction of oestrogenic activity was reached	Alum et al., 2004
Diclofenac	Distilled water	Ozonization	pH 5.0; 5.5 and 6.0; scavenger = *tert*-butyl alcohol; *C*0 = 0.1 mmol l^{-11}; *C*O3 aqueous = 0.1 mmol l^{-11}	100% of chlorine release was observed and 32% mineralization	Vogna et al., 2004
Natural oestrogen (17β-Estradiol)	Distilled water	Ozonization	C_0 = 5.2 μmol l^{-1}; *T*=20 C; contact time 30 min; CO3 = 5.0 15 mg l^{-1}; pH 6.0; experiments with and without fulvic acid	99% removal of 17β-Estradiol with ozone dose of 5 mg l^{-1} in 15 min or ozone dose of 15 mg l^{-1} in 4min. A reduction of oestrogenic activity was observed	Kim et al. 2004
Synthetic oestrogen (17α-Ethinyloestradiol)	Milli Q purified water	Ozonization	C0 = 1 a 10 μmol l^{-1}, pH 8; C_{O3} = 5 a 24 μmol l^{-1}; C_{O3} = 50 a 100 μmol l^{-1}	Oxidation products formed during the ozonization of 17α-Ethinyloestradiol were identified. Ozone doses ranging from 0.5 up to 10 mg l^{-1} removed oestrogenicity.	Huber et al., 2004
Antibiotic (amoxicillin)	Aqueous solution	Ozonization	C_0 = 0.5 mmol l^{-1}; C_{O3} = 0.16 mmol l^{-1}, pH 2,5-5,0	Low mineralization and some by-products were identified	Andreozzi et al.,2005

Compound	Type of water	Treatment	Operation Conditions	Results and Commentaries	Reference
Natural oestrogen (17β-Estradiol)	Milli Q and distilled water	Ozonization	C_0 = 10 and 50 μg l^{-1}, pH 3.7 and 11; C_{O3} = 0,5 a 30 mg l^{-1}	The results show that ozonization was able to promote extensive degradation of 17β-Estradiol and to reduce its oestrogenic activity. The results showed that in pH 7 and 11 the oestrogenic activity was not completely removed, even with an increase of the dosage of ozone	Bila et al., 2005
Natural oestrogen (17β-Estradiol) and bisphenol (bisphenol A)	Aqueous solution	Ozonization	C_0 = 0,10 mmol l^{-1}; C_{O3} = 7,516 μmol l^{-1}	The reaction between bisphenol A and ozone is slower than the reaction between 17β-Estradiol and ozone	Irmak et al., 2005
Pesticide (atrazine) pharmaceuticals (carbamazepine)	Drinking water	Ozonization	pH 7,5; C_{O3} = 1.52.0 mg l^{-1}	High efficiency in removing micropollutants using ozonization after filtration and coagulation/flocculation	Hua et al., 2006
Antibiotic (clarithromycin)	Milli Q water	Ozonization	C_0 = 0,1 mmMol l^{-1}; C_{O3} = 10 μmol l^{-1}, T = 20 ºC	Biological activity of clarithromycin was reduced after ozonization	Lange et al., 2006
Pesticides (alachlor, atrazine, chlorfenvinphos, isobroturum, diuron)	Distilled water	Ozonization	C_{O3} = 26.8 g m^{-3}; C_0 = 16-20 mg l^{-1}	Large amounts of ozone were spent to remove pesticides. Complete removal of TOC was hard to achieve	Maldonado et al., 2006
Benzafibrate (lipid regulator)	Distilled water	Ozonization	C_{O3} = 1 μmol l^{-1} C_0 = 0.2-0. μmol l^{-1}, pH 6 to 8	Complete BZF abatement is achieved. However, only a small part of the substrate is mineralized	Dantas et al., 2007
Ibuprofen, bezafibrate, amoxicillin, sulfamethoxazole	Pure water	Ozonization	C_0= 10 μnol l^{-1}	In the ozone-Membrane Filtration hybrid experiments, the pre-ozonization was able to reduce the membrane fouling	Soo Oh et al., 2007
17β-Estradiol 17α-Ethinyloestradiol	Milli Q water	Ozonization O_3/H_2O_2	C_0= 10 μg l^{-1} (17μ-Estradiol) C_0= 10 μg l^{-1} (17α-Ethinyloestradiol) 2:1 O_3/H_2O_2 relation	99.7% and 98.8% were removed at pH 11 separately while 100% and 99,5% were eliminated at pH 3 for 17β-Estradiol and 17α-Ethinyloestradiol, respectively Total oestrogenic activity was removed at pH 3 for ozonization o O_3/H_2O_2 process	Guedes et al., 2008
Bisphenol A	Milli Q water	Ozonization	C_0=100 μM -100 μ mL C_{03}=15-400 μM	Reaction subproducts were analyzed and identificated: catechol, ortoquinone, muconic acid, benzoquinone and 2-(4-hydroxyphenyl)-propan-2-ol	Deborde et al., 2008

Compound	Type of water	Treatment	Operation Conditions	Results and Commentaries	Reference
Phenazone, ibuprofen, Diphenhydramine, phenytoin, diclofenac	Distilled water	Catalyst Ozonization	C_0=3 mg l^{-1} C_{03}=30 mg l^{-1} MnOx supported by mesoporous alumina (MnOx/MA)	MnO_x catalyst allows formation and activation of surfaces hydroxyl groups; it produced a high catalytic reactivity. Catalyst was highly effective in pharmaceuticals degradation in aqueous solution	Yang et al., 2009

TOC: Total Organic Carbon
TPSW: Treatment plant for sewage water

potential disruption effects of ECs on living things are still uncertain and require further investigation.

The need for identification and analysis of EDCs has caused the development of analysis methods that use tools like *chromatography of gases* (CG) or *chromatography of liquids* (CL) coupled with *spectrometry of masses* (MS) detection; the most commonly used are GC/MS, GC/MS/MS in sequence, and LC/MS/MS. The use of the solid-phase extraction technique reduces time and resources compared to conventional methods.

There are a great number of *advanced oxidation processes* (AOPs) that are being investigated at a laboratory level for degrading EDCs and recalcitrant or poorly biodegradable organic material in general. However, AOP-O_3 are the most studied of the high-efficiency processes (higher than 80 per cent) obtained in relatively short times – within minutes. In addition, AOP-O_3 have lower costs with respect to other AOPs in the generation of $OH^{\bullet}$ radicals. AOP-O_3 are capable of achieving partial or total oxidation (mineralization) of the organic material; the level of oxidation diminishes the possibility of forming by-product compounds that are harmful to health. It should be mentioned that the times and concentrations of ozone necessary for the oxidation of EDCs vary according to the nature of the compound.

Finally, the use of AOP-O_3 promises to be one of the most appropriate technological resources not only for the treatment of surface water containing EDCs, including hormones and pharmaceuticals, but in general for industrial effluents contaminated with compounds of low biodegradability such as dyes, lignins from paper mill effluents, phenolic compounds, detergents, organochlorine compounds, and beauty products. Despite the effectiveness of AOP-O_3, it is necessary to perform a technical evaluation of costs and benefits to verify that AOP-O_3 are technologically and economically viable.

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22 Biodegradation of a Reactive Red Azo Dye in an Upflow Anaerobic Bioreactor

Linda González and Eleazar Escamilla Silva

22.1 Introduction[1]

Xenobiotic dyes used by the textile industry are highly pollutant as they have been the object of several studies. Reactive dyes are highly soluble in water due to the sulphonated groups in their molecules. This chapter presents the results of a study on the degradation of reactive red azo dye 272 under anaerobic conditions in an *upflow sludge bed reactor* (UAFB) with an activated carbon-biomass fixed bed, using an adapted consortium of microorganisms. This degradation mechanism is abiotic-biotic, due to processes of adsorption (activated carbon), biosorption (biomass), and biochemical reactions.

The operational conditions under which the dye was degraded were studied in flask tests. Solution pH for dye removal was analysed using activated carbon as a support to form biofilms and as a redox mediator for the reduction reaction. The amounts of activated carbon and biomass used were the key factors in degradation, achieving larger removal rates at pH 5 (from 87 to 99 per cent). The experimental design applied to the reactor in continuous operation indicated that the most significant factors related to degradation efficiency are: initial dye and dextrose concentrations related to dye removal rates, and residence time in the reactor for *chemical oxygen demand* (COD) removal rates.

The reduction kinetics were studied in batch tests and in continuous operation in the reactor. It was observed that the reaction rate is reduced as dye concentration is increased; in addition, the profiles of dye concentration vs. time revealed a non-lineal behaviour. Therefore, an order-change kinetic model was proposed for dye reduction.

1 Keywords: reactive azo dye, anaerobic degradation, fixed bed reactor, biodegradation pathways, dynamic model.

Dye degradation products were identified in the reactor effluent; they were essentially aliphatic compounds: carboxylic acids, alcohols and amides. It was also possible to find aromatic compounds such as phenol and naphthalene, but this largely depended on the residence time in the reactor. Accordingly, biodegradation pathways for the azo dye were proposed.

Residence time distribution was studied and a dynamic model was proposed for the reactor. With the results, a mathematical model was proposed. It is based on the general balance of the dye flux along the reactor and in a balance for the bioparticle which comprises two regions: the activated carbon core and the biofilm. The model considers that the reaction is carried out in the liquid phase and in the biofilm by means of the kinetic model previously proposed.

The model predicts the dye profiles along the reactor and within the bioparticle for different initial dye concentration and different reactor residence times (RT_m). These profiles reveal a fast saturation and fast equilibrium and predict lower removal rates as dye concentration increases in the influent. The change in dye concentration does not significantly affect the profile within the bioparticle, but removal efficiency in the reactor is reduced, contrary to the results of a change in RT_m which does not influence the concentration profile in the reactor, but does affect the profile within the bioparticle, increasing the saturation rate.

In the UAFB reactor, degradation occurs through a process of adsorption-biodegradation. *Activated carbon* (AC) adsorbs and interacts as redox mediator. Thus, degradation of the azo dye through this process is abiotic-biotic.

The textile industry uses significant volumes of water, and so it generates significant heavily polluted discharges.The process of dyeing and printing industries is the most important source of dye in their wastewater; the concentration of dyes in water discharges

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*, Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_22,

from textile industries varies between 100 and 500 mg/l (Sponza and Işik, 2004).

The most widely used dyes in textile industries are azo dyes. Their most important characteristic is an unsaturated bond of two nitrogen molecules -N=N- (azo); these molecules may contain one or more azo groups and each bond is generally tied to an aromatic group. These compounds are classified as reactive, metallic, disperse, basic, acid, direct, and mordant. Reactive dyes are the hardest to remove due to the structure of their molecule and its groups, such as 3,6-naphthalene-disulfonate and chloro-triazines. Molecules of azo compounds are very stable and in order to degrade them they first have to be reduced and their intermediary products partially or totally mineralized; this is very important as intermediary products of many azo dyes are carcinogenic or highly toxic (Chacón et al., 2002), for example benzidine, 2-naphthylamine and other aromatic amines.

Some processes for degrading azo dyes have been suggested, for example anaerobic bioreduction. In order for reduction to take place, the molecule must accept electrons in the reaction. The problem with anaerobic degradation is that kinetics are slow, thus in order to make anaerobic processes more efficient, substances and materials that act as redox mediators and accelerate reduction and degradation have also been researched. The limiting factor in the degradation of these compounds is the transference of electrons; four electrons are necessary in order to break an azo bond. Redox mediators that have been analysed are humic substances rich in quinones such as *anthraquinone 2,6-disulfonate* (AQDS), amongst others (Field et al., 2000; van der Zee et al., 2000; Cervantes et al., 2001, 2003).

Water polluted with these compounds can be treated through bioreactors similar to those used conventionally, but only after improving the process with the stimulus of microorganisms adapted for degradation of the specific dye in order to make its reduction efficient. Razo-Flores et al. (1997) demonstrated that some azo dyes can become sources of carbon, nitrogen, and energy for anaerobic microorganisms, hence they can be degraded in biological reactors; for this, the authors used an *Upflow Anaerobic Sludge Blanket* (UASB). Also using a UASB, Cervantes et al. (2001) managed to degrade acid orange 7, while Tan et al. (2000) degraded mordant yellow 10 in a sequential anaerobic-aerobic process. UASB reactors have also been used in the degradation of various other azoic dyes (Razo-Flores et al., 1997; Willetts et al., 2000; Van der Zee et al., 2001, 2003; Cervantes et al., 2001; Işik/Sponza, 2005), where it is necessary to use electron donor substances (glucose, ethanol) and/or redox mediators.

The use of a support media to fix microorganisms in bioreactors has been proven in order to provide them with a surface for growth and protection from inhibiting substances. These support media should preferably have a rough and highly porous surface, just like *activated carbon* (AC), which has been widely used for fixing microorganisms in bioreactors that are used to remove and degrade toxic pollutants (Duan et al., 2005; Carvalho et al., 2006; Mezohegyi et al., 2007). The use of activated carbon benefits the reduction of azo dyes as it provides an adequate surface for microorganisms to grow; it is an effective adsorption matrix and the chemical groups on its surface is acting act as redox mediators (van der Zee et al., 2003; Mezohegyi et al., 2007).

The current project proposes solving the problems of azo dyes in wastewater for the textile industry through an anaerobic upflow reactor with an activated carbon-biomass fixed bed, using an adapted consortium of microorganisms as biofilm, in order to improve cellular retention in the reactor and efficiency of the overall process. The kinetic study and degradation mechanism of a reactive red azo dye will be described, as well as transport within the reactor, by means of a mathematical model.

22.2 Objectives

The general objective of this study is to establish the optimal conditions for degradation of reactive red azo dye 272 in an anaerobic upflow sludge bed reactor with an activated carbon-biomass fixed bed, analysing the kinetics of reduction and characterizing the reactor, in order to propose a feasible process to treat wastewater from textile industries. Specific objectives were:

a.) to adapt a group of microorganisms to the conditions of wastewater from the textile industry enriched with reactive red azo dye 272 in order to make its degradation effective;
b.) to establish the best possible conditions for degradation of reactive red azo dye 272 through flask tests;
c.) to obtain isotherm and adsorption parameters of this dye with activated carbon;
d.) to characterize an anaerobic upflow sludge bed reactor with a fixed bed, using activated carbon in

order to fix microorganisms and augment efficiency; to obtain the parameters for the operation;

e.) to explain the kinetics and reaction mechanisms of degradation of reactive red azo dye 272; for this, to identify the products following a reduction of the dye at the exit of the bioreactor using instrumental analytical tools; and

f.) to analyse mass transport and hydrodynamics in the reactor as well as to elaborate and solve a mathematical model in order to describe and predict the behaviour of the reactor.

22.3 Methodology

22.3.1 Preparation of the Inoculant and Maintenance Conditions

A consortium of microorganisms was adapted to wastewater from a wool textile industry that uses reactive azo dyes. Six litres (6 l) of wastewater from the dyeing process were taken, 5 per cent V/V of cow dung, 1.5 per cent v/v of yeast extract, and 20,000 mg/l dextrose were added. During the preparation process, pH, COD, and *volatile suspended solids* (VSS) were monitored. To maintain the inoculant, 1000 mg/l of yeast extract, 1000 mg/l dextrose, and 2000 mg/l of reactive red 272 (model molecule) were added weekly.

22.3.2 Decoloration of the Reactive Red Azo Dye 272 in Batch Studies

The reactive red azo dye 272 was chosen as the model molecule. Decoloration tests for reactive red were undertaken in a 500 ml flask, using as inoculants the adapted consortium of microorganisms (20, 30, 40 ml), activated carbon (10, 20, 30 mg), *tetrahydroquinone* (THQ: 400, 40, 4 mg), and the dye in the following concentrations: 100, 550, 1000 mg/l. A factorial-orthogonal design L9 was used in order to study the effects of the variables in degradation. The studies were undertaken both controlling and without controlling pH at 5.

22.3.3 Adsorption Isotherms of the Dye over AC and Characteristics of AC

In order to know the adsorption capacity of the dye over activated carbon, tests were undertaken using one gramme of activated carbon in conjunction with 500 mL solutions with different concentrations of red azo dye (10, 100, 500, 800 and 1000 mg/l). The solutions were kept until they reached an equilibrium – which was when the concentration of the dye in the solution remained constant – which took 5 days. For this, samples were taken at different times and the concentration of the dye was measured in the solution with absorbance measured at 506 nm. Carbon used was of vegetal origin; its characteristics are displayed in table 22.1. The concentration of active groups in the AC surface was measured using the Boehm titration method (Boehm, 1966, 1970, 1994). The amount of adsorbed mass was calculated through a mass balance and data obtained were adjusted using the Freundlich model, which is mathematically expressed by equation 1 where k is a constant that indicates adsorption capacity and 1/n is the intensity of adsorption (Cooney, 1999). Parameters were adjusted using the software Statistica 6 (© StatSoft, Inc. 2000).

$$q = kC_e^{1/n} \qquad (1)$$

22.3.4 Flask Test Kinetic Study

In Erlenmeyer flasks of 500 ml, 1 g of AC and 5 ml of the inoculant were mixed (2 per cent v/v), containing approximately 6.6 g/l total solids. Following this, 250 ml of reactive red azo dye 272 were added, varying the concentration between 100 and 500 mg/l with or without 1 g/l dextrose. The flasks were left in an orbital shaker with a 30°C temperature control, and 10 ml samples were taken at 0, 3, 6, 12, 24, 48, 72 and 96 hours. Given the changes in dye concentrations, the absorbance was measured at 506 nm and COD was determined. Finally, a kinetic model to represent decoloration data was proposed.

22.3.5 Reactor Set up and Tests

A Pyrex reactor with an *upflow anaerobic fixed bed* (UAFB) was set up, with a fixed bed of AC of 42 per cent of total volume (541.17 g of AC). The characteristics of the reactor are shown in table 22.2, with a diagram in figure 22.1. The AC bed was saturated with red dye (re-circulating the solution with dye in concentrations of 500 and 1000 mg/l) in order not to attribute decoloration only to a possible adsorption in activated carbon. Afterwards, it was inoculated with an adapted anaerobic consortium. An experimental design 2^4 was undertaken in order to determine factors that affect degradation of reactive red azo dye under different conditions: flow 18 and 32 ml/min (residence time 3–5 h), dye concentration 250 and 500

Table 22.1: Characteristics of activated carbon utilized. **Source:** Authors' research results.

Raw material	Coconut peel
*Activation method	Vapour
*Density, g/cm^3	0.45-0.42
*Surface area, m^2/g	550
*Average diameter of particle, mm (granulometry)	1.03 (12/40)
* Pore volume, ml/g	0.32
Particle porosity ε_p	0.139
Average pore diameter, Å	23.3
Acid sites, meq/g	2.66
Basic sites, meq/g	0.15
Water adsorption, g H_2O/g CA	2.27
Humidity	6.8%

* Data given by the supplier (Clarimex)

mg/l, dextrose 500 and 1000 mg/l, yeast extract 500 and 1000 mg/l. Dextrose and yeast extract were used as electron donor and nutrients.

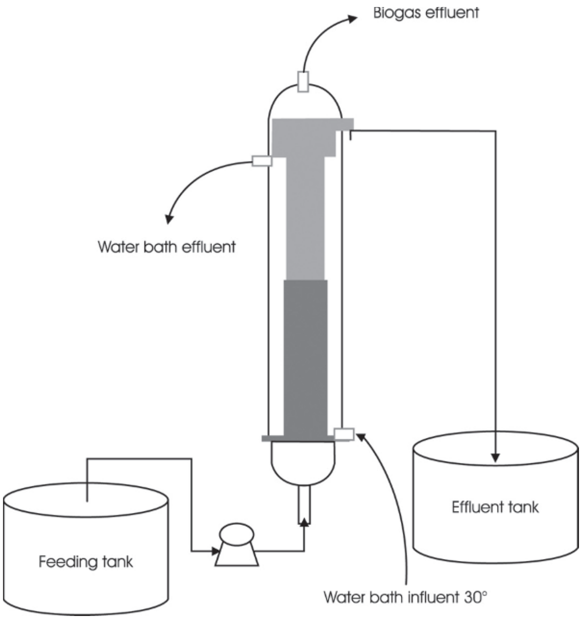
Table 22.2: Characteristics of the UAFB Reactor. **Source:** Authors' research data.

Working volume (l)	3
Internal diameter (cm)	6
Sedimentator internal diameter (cm)	9.5
Total length (cm)	105.5
Initial bed porosity	0.53
Bed porosity at a stable stage	0.19
Fixed bed volume (l)	1.24
Average surface speed (cm/min)	0.52
Average flow (ml/min)	18
Average residence time (min)	206.25

22.3.6 Identification of Compounds

In order to identify the products of degradation, samples of the effluent were taken under different operating conditions. Samples were extracted with ethyl acetate; the extract was rotary evaporated by gas chromatography – mass spectrometry with Perkin Elmer Clarus 500 GC equipment. The method used consisted in keeping a temperature of 40°C for 8 minutes followed by a temperature ramp of 5 minutes until a temperature of 250°C was reached for 30 minutes. The results were analysed using TurboMass

Figure 22.1: Upflow Anaerobic Fixed Bed (UAFB) reactor. **Source:** Research design developed by the authors.



version 5.0.0; mass spectra of identified compounds were corroborated with the NIST Mass Spectral Database.

22.4 Results

In order to study the anaerobic degradation of azo dyes in the proposed bioreactor, reactive red 272 was treated as a model compound; its molecule is shown in figure 22.2. First, flask tests were undertaken to determine the effect of activated carbon, of dextrose as electron donor, and of yeast extract as microorganism nutrient. Afterwards, kinetics were studied and a fixed bed reactor was designed in order to analyse efficiency, identify effluent compounds, study transport phenomena, and put forward the mathematical model.

22.4.1 Flask Tests (Batch)

Experimental design L9 was undertaken at a pH of 7 and a pH of 5 in order to analyse the effects of slightly acidic pH in degradation efficiency since, depending on its molecular structure (number of azo bonds, type and number of functional chemical groups), this condition can accelerate the reduction of azo dyes (Ramalho et al., 2004). The results obtained by the tests are displayed in table 22.3. The average COD removal

Table 22.3: Batch test conditions and results at different pH levels (pH 7 and pH 5). **Source:** Authors' research results.

Test number	C_0 mg/l	Inoculant ml	AC G	THQ mg	COD % R pH 7	COD % R pH 5
RL1	100	20	10	4	93.02	88.52
RL2	100	30	20	40	90.47	91.13
RL3	100	40	30	400	90.11	85.62
RL4	550	20	20	400	93.33	96.79
RL5	550	30	30	4	92.67	94.04
RL6	550	40	10	40	59.17	83.00
RL7	1000	20	30	40	83.50	91.91
RL8	1000	30	10	400	59.61	87.00
RL9	1000	40	20	4	53.75	91.42

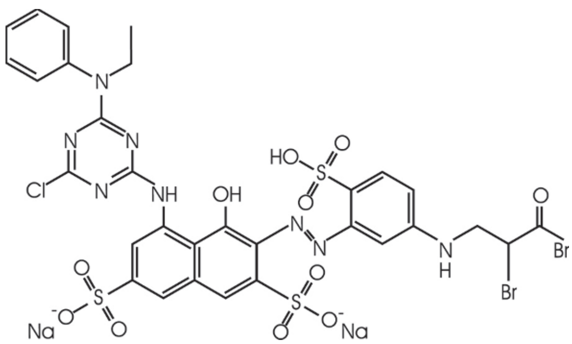
AC: *Activated Carbon*, C_0: *initial dye concentration*, THQ: *Tetrahydroquinone*, COD: *per cent R: removal rate*

Table 22.4: Analysis of variance for experimental design in flasks at pH 7. **Source:** Authors' research results.

Factors	S. S.	D. F.	M. S.	F	P
Concentration	2006.92	2	1003.46	52.6814	0.00001
Inoculant	1506.18	2	753.090	39.5371	0.00004
Activated Carbon	990.687	2	495.343	26.0054	0.00018
THQ	33.5640	2	16.7820	0.88105	0.44725
Error	171.429	9	19.0480		
Total S.S.	4708.78	17			

R^2= 0.964. S.S.: *Sum of squares*; D.F.: *Degrees of Freedom*; M.S.: *Mean Squares*;
F: *Probability distribution value*; P: *P-value*.

Figure 22.2: Reactive Red Azo Dye 272. **Source:** Authors.



that was achieved ranged from 53.75 to 93.02 per cent with pH 7, and from 85.62 to 96.79 per cent controlling at pH 5. On average, with pH 5 it is possible to attain a higher removal rate than with pH 7. This observation has to do with the fact that at lower pH levels one finds greater concentration of H_3O^+ ions as six protons are consumed when the azo bond breaks (Ramalho et al., 2004).

Table 22.4 shows the analysis of variance results obtained by statistical analysis for the experimental design at pH 7, highlighting factors that most affect dye removal, such as initial concentration, inoculant concentration (biomass), and activated carbon. Table 22.5 shows factors that affected dye removal at pH 5, including amounts of AC and of the inoculant.

The observed AC effects are due to the fact that during the first stage of dye removal, adsorption and bioadsorption take place, as well as the start of the biochemical reaction. When there is higher amounts of AC, the more surface adsorption occurs, enabling the formation of the biofilm by microorganisms. A sample of AC used was taken and analyzed for volatile suspended solids total were 159.1 mg VSS/g AC, which corresponds to the biomass fixed to carbon as biofilm.

These effects have other implications: i) the presence of an electron donor benefits decoloration but it is not a determining factor in order to take place, and ii) a decrease in pH also implies an increased redox potential in the environment, which enhances decoloration.

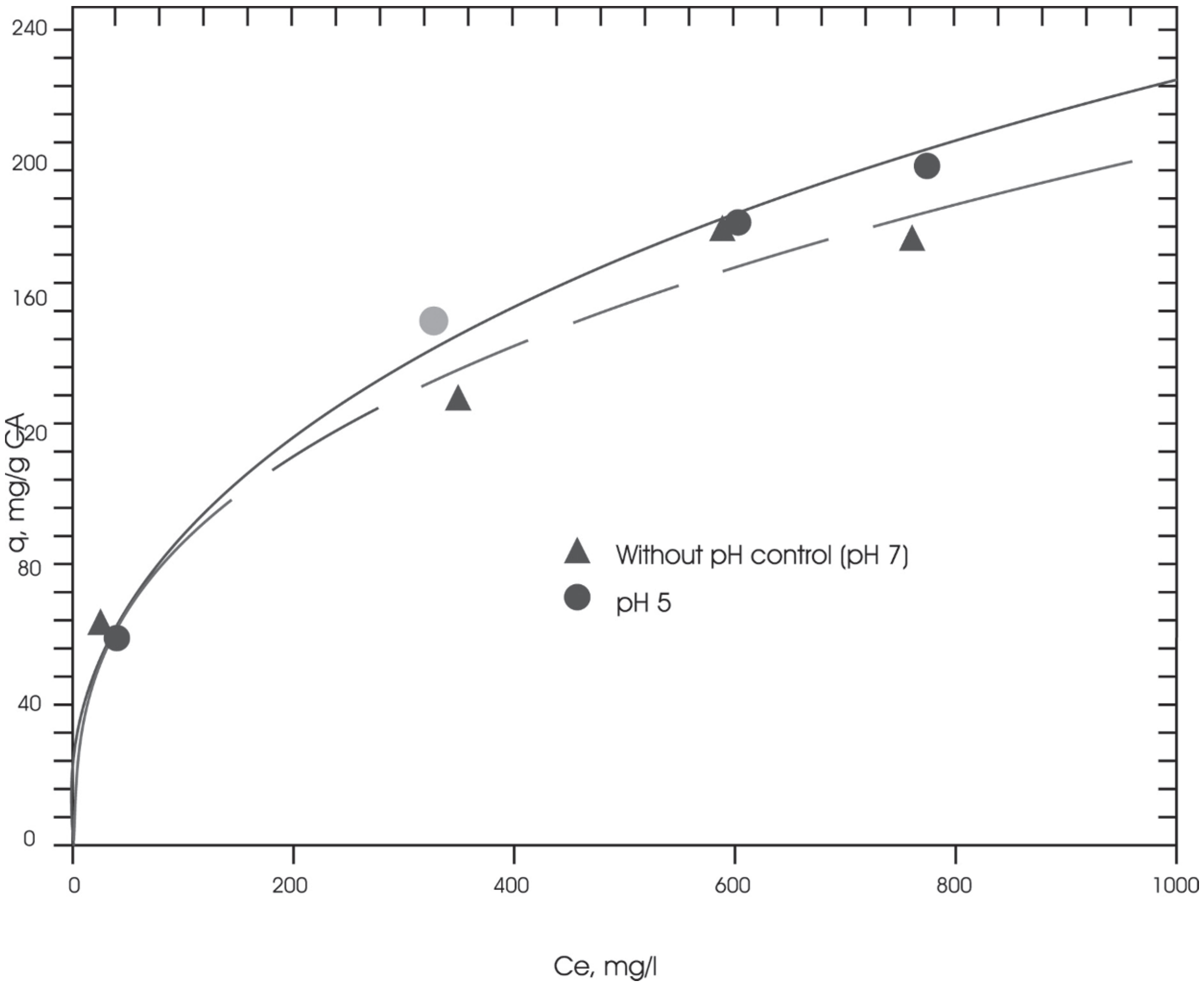
Adsorption isotherms were obtained at pH 7 and pH 5. The maximum adsorption capacity of AC was 211 mg/g at pH 7. Adsorption isotherms were best represented by the Freundlich model shown in figure 22.3. The constants were: k = 14.4 and 16.21 l/mg, 1/

Table 22.5: Analysis of variance for experimental design in flasks at pH 5. **Source:** Authors' research results.

Factors	S. S.	D. F.	M. S.	F	P
Concentration	24.7363	2	12.3681	1.24278	0.33374
Inoculant	103.926	2	51.9628	5.22134	0.03124
Activated Carbon	147.675	2	73.8375	7.41935	0.01248
THQ	21.1841	2	10.5921	1.06432	0.38468
Error	89.5681	9	9.95201		
Total S.S.	387.089	17			

R^2= 0.77. S.S.: Sum of Squares; D.F.: Degrees of Freedom; M.S. Mean Squares;
F: Probability distribution value; P: P-value

Figure 22.3: Adsorption isotherms at pH 7 and 5 (Temperature 28-30°C). **Source:** Authors' research results.



n = 0.394 and 0.362, without pH control and with pH5 respectively.

22.4.2 Kinetic Model

The kinetic model proposed to represent decoloration of reactive red 272 is expressed by equation 2. It is an order-change kinetic model, based on the observation that when the amount of reduced dye aug-

Figure 22.4: Experimental data adjusted to the kinetic model for flask tests at 250 and 500 mg/l. C/C0 = dimensionless concentration. **Source:** Authors' research results.

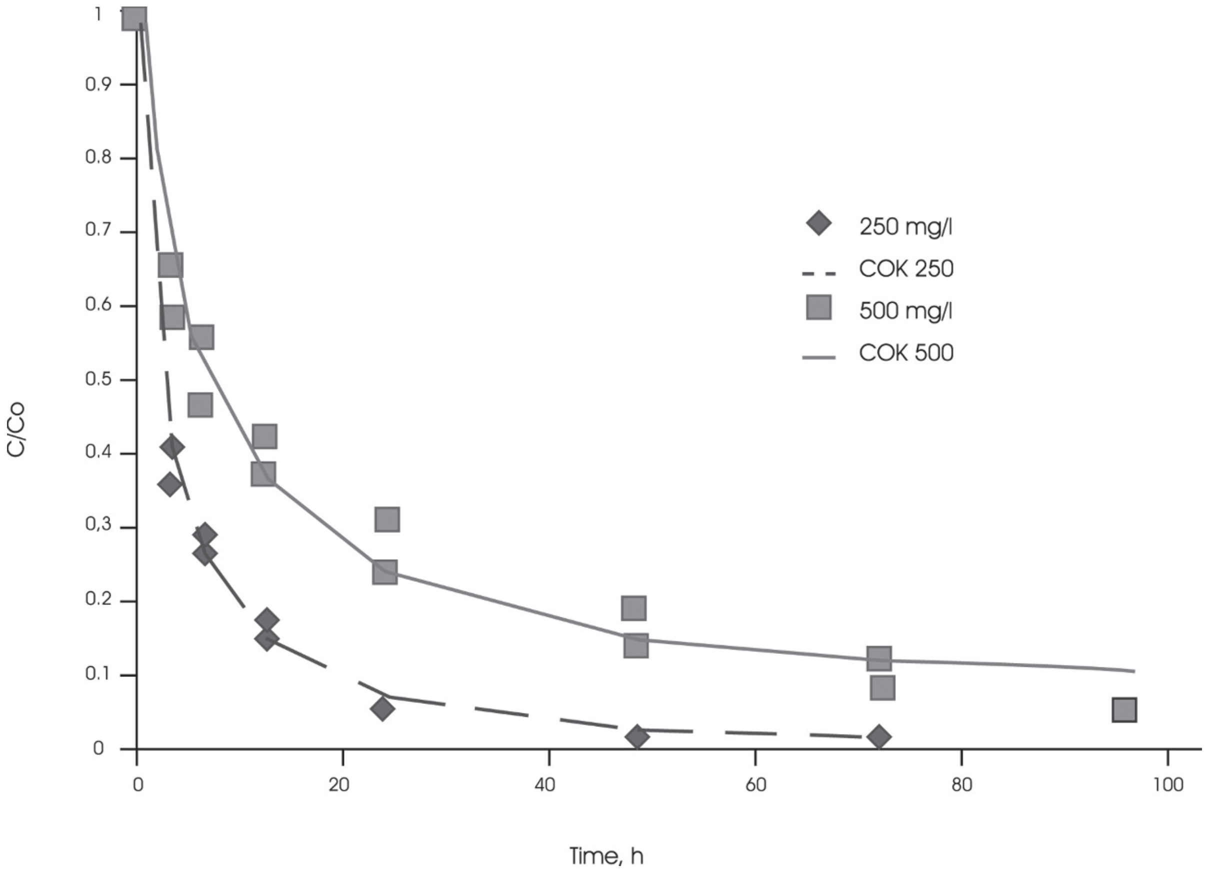


Table 22.6: Conditions and results of kinetic tests in flasks. **Source:** Authors' research results.

Test number	C_{A0} Mg/l	Dex mg/l	k_1 h^{-1}	$k_2 \times 10^{-3}$ l/mg h	% R Colour	% R COD	R^2 OCK
CM100	100	-	1.164	10.30	100.0	80.00	0.9948
CM250	250	-	0.451	1.680	98.98	62.50	0.9952
CM300	300	-	0.349	1.080	99.59	62.50	0.9899
CM400	400	-	0.201	0.540	94.06	75.00	0.9854
CM500	500	-	0.155	0.333	91.29	50.00	0.9753
CDx100	100	1000	1.551	13.63	100.0	15.63	0.9988
CDx250	250	1000	0.403	1.490	99.16	75.00	0.9972
CDx300	300	1000	0.356	1.090	99.74	42.50	0.9933
CDx400	400	1000	0.228	0.589	95.96	53.13	0.9891
CDx500	500	1000	0.252	0.564	94.40	66.25	0.9431

Per cent R: *removal percentage*; OCK: *Order-Change Kinetics*; Dex: *Dextrose*

ments (decoloration), a reduction in the reaction rate can be observed. Besides this, time profiles obtained indicate a non-linear behaviour.

$$r_A = -\frac{dC_A}{dt} = k_1 C_A - k_2 C_A (C_{A0} - C_A) \qquad (2)$$

In the equation, C_{A0} is the initial dye concentration; k_1 is the specific first-order reaction rate; and k_2 is the second order rate constant.

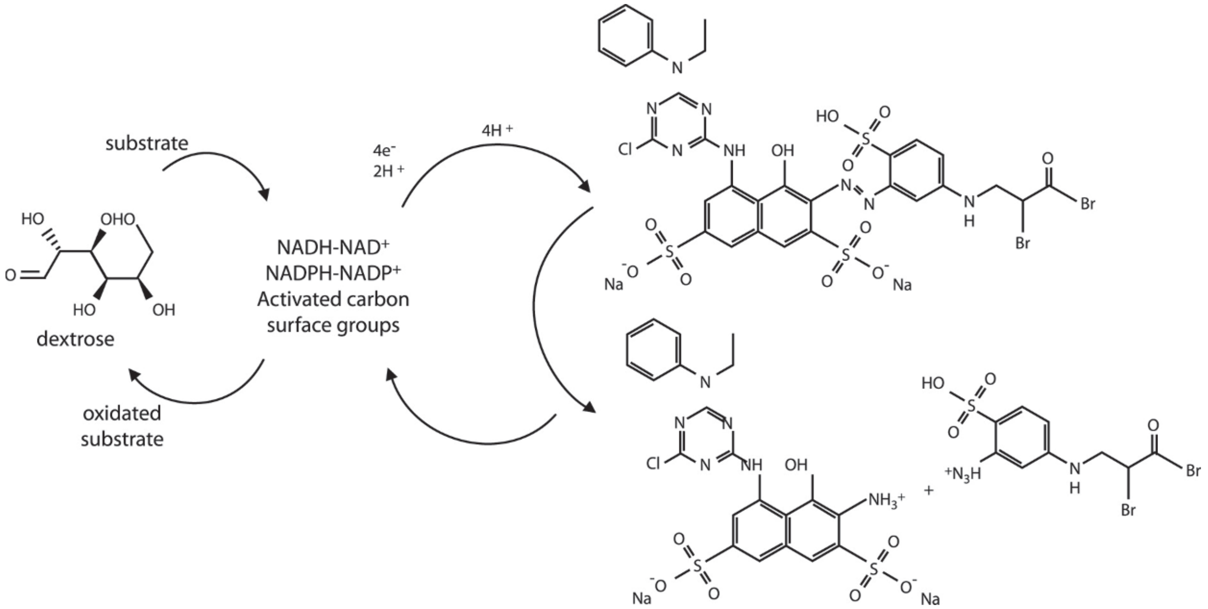
This model presented was deduced based on the analysis of experimental data obtained following several studies measuring dye reduction in relation to time and comparing it with other models. The model

Table 22.7: Operating conditions of the tests according to the experimental design, obtained colour and COD removal rates. **Source:** Authors' research results.

Number	Q ml/min	C_0 colour	C_0 dextrose	C_0 yeast	OC kg/m^{3}d	% R COD	% R colour
1	18	250	500	500	12.77	52.3	97.2
2	32	250	500	1000	23.91	30.0	97.8
3	18	500	500	1000	18.19	53.3	98.6
4	32	500	500	500	19.12	36.1	98.6
5	18	250	1000	1000	30.26	56.0	91.4
6	32	250	1000	500	44.30	37.7	91.5
7	18	500	1000	500	23.53	55.0	97.7
8	32	500	1000	1000	35.86	16.3	96.6

Per cent R: removal rate (percentage); OC: Organic charge; C_0: initial concentration in mg/l

Figure 22.5: Reduction in the dye molecule. First step in degradation. **Source:** Authors' research results. **Legend:** PM: molecular weight.



proposed best represents the information obtained regarding the entire process. It confirms that at lower dye concentrations, dye reduction follows first-order kinetics, whereas at higher concentrations it follows second-order kinetics. As was expected, at the entry to the reactor concentration is higher and it markedly decreases as water ascends; thus, the best way to represent these types of reactions is with an order-change kinetic model. The model accurately represents a reduction of reactive red 272 at high concentrations (above 400 mg/l), which gives it more relevance. Industrial textile wastewater usually does not have concentrations higher than 500 mg/l. Another explanation that accounts for the change from the first to the second order is that at first decoloration is due to adsorption and bioadsorption of the dye and the start of the biochemical reaction (this represents the first order), and subsequently we have the reduction reaction (this represents the second order).

The adjustment of experimental data to the kinetic model is shown in figure 22.4 for an initial concentration of 250 and 500 mg/l (without dextrose). The results of kinetic tests in the flasks, varying the initial concentration of the dye from 100 to 500 mg/l, and using activated carbon as the inoculant of adapted microorganisms – with and without dextrose – is shown in table 22.6.

Empirical data showed that specific reaction rates k_1 and k_2 decrease as dye concentration increases, i.e., the reaction becomes slower as the concentration of dye in the water increases, even with dextrose. Nev-

Figure 22.6: Compounds identified in the reactor's effluent in degradation conditions with COD removal of ~50 per cent (TRH 4-5 h). **Source:** Authors' research results.

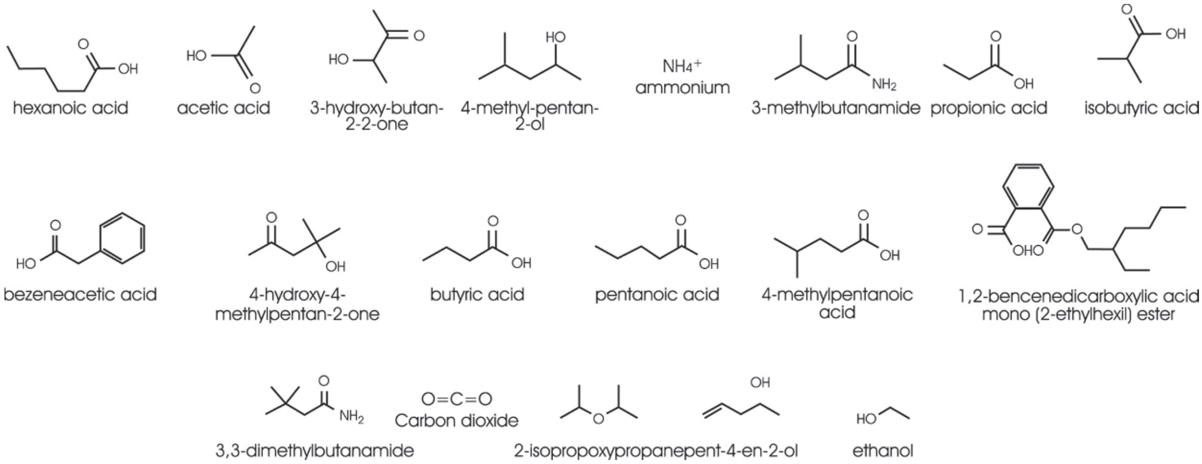
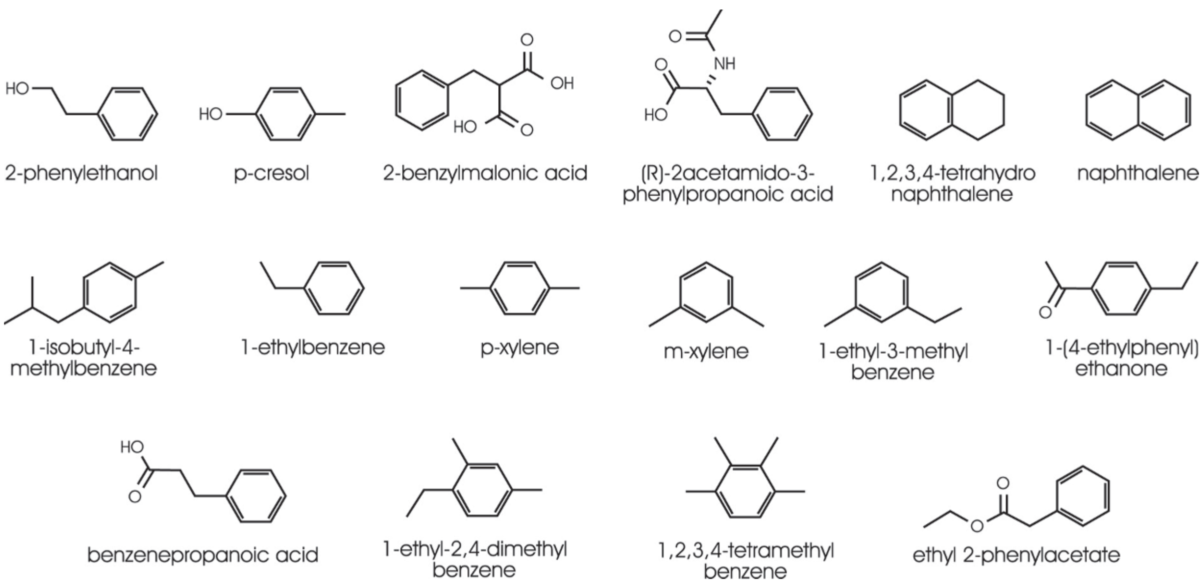


Figure 22.7: Aromatic compounds found in the reactor's effluent when decreasing residence time or increasing dye concentrations. **Source:** Authors' research results.



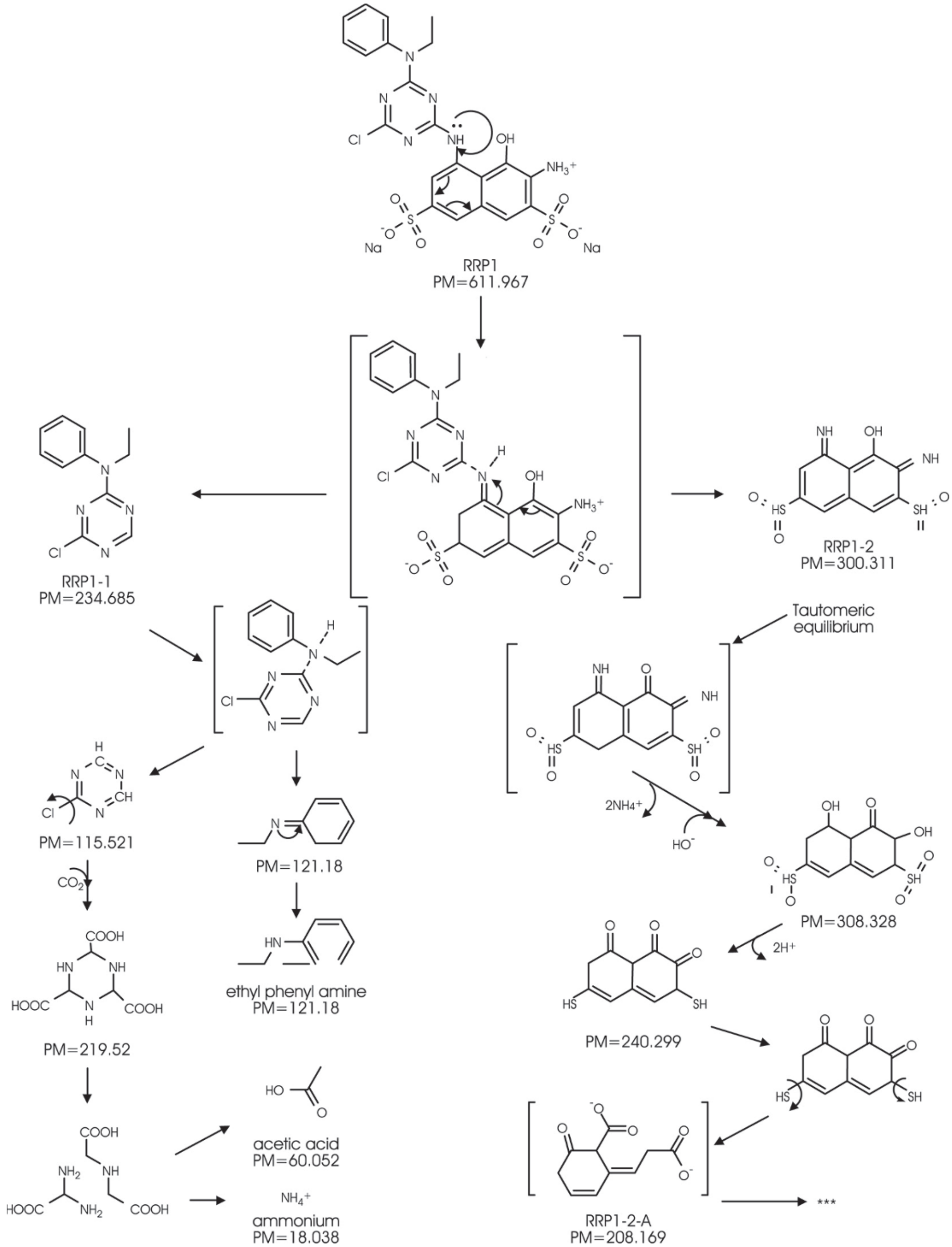
ertheless, the values of these constants increased with the use of dextrose, for each concentration.

22.4.3 Studies in the Upflow Anaerobic Sludge Bed Reactor (UASB)

Following the results obtained in flask tests, the most important factors for degradation of red dye were identified. With these, the conditions for using it in the upflow anaerobic sludge bed reactor with activated carbon were determined; it was operated controlling pH at 5 and temperature between 28 and 30°C. In the inoculation of the reactor, 11.6 mg VSS/g AC was adsorbed and fixed to the AC surface, forming the biofilm. The growth of microorganisms over the reactor's surface continued during the operation phase; average thickness of the biofilm and concentration of biomass in the reactor at later stages depend on the speed of surface flow within the reactor; these parameters were not determined experimentally.

In the experimental tests, the results obtained for dye removal were between 91.4 and 98.6 per cent, wile COD removal was between 16.3 and 56 per cent. These results are shown in table 22.7 together with the operating conditions for each test. The COD removal rates obtained are an indicator of the degree of degradation of the dye and of aromatic compounds derived from its reduction, which is why they are

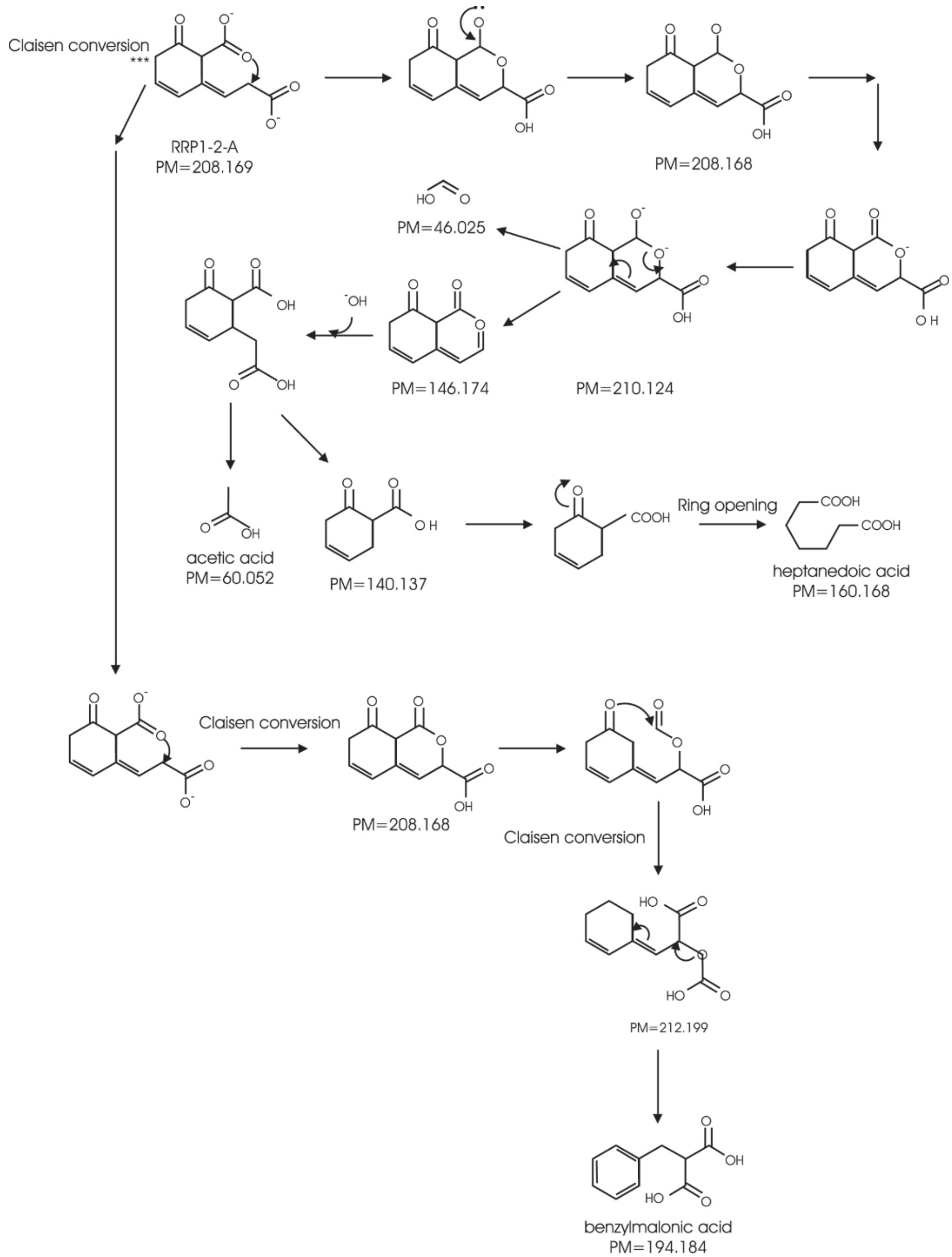
Figure 22.8: Proposed RRP1 degradation route. **Source:** Authors' research results. **Legend:** PM: molecular weight.



lower than colour removal. The highest degree of degradation was obtained operating at greater residence times (5 h)

According to the results of the experiment, determining factors in colour removal in the reactor were dye concentrations in the influent and dextrose concentrations. Dextrose added to the water is important in so far as it is the carbon source for microorganisms and it donates electrons, improving degradation of these kinds of dyes (van der Zee et al., 2003; Hong et al., 2007). In order to remove COD, the most important factor is the working flow, i.e., the residence time

Figure 22.9: Proposed RRP1-2-A degradation route. **Source:** Authors' research results. **Legend:** PM: molecular weight.

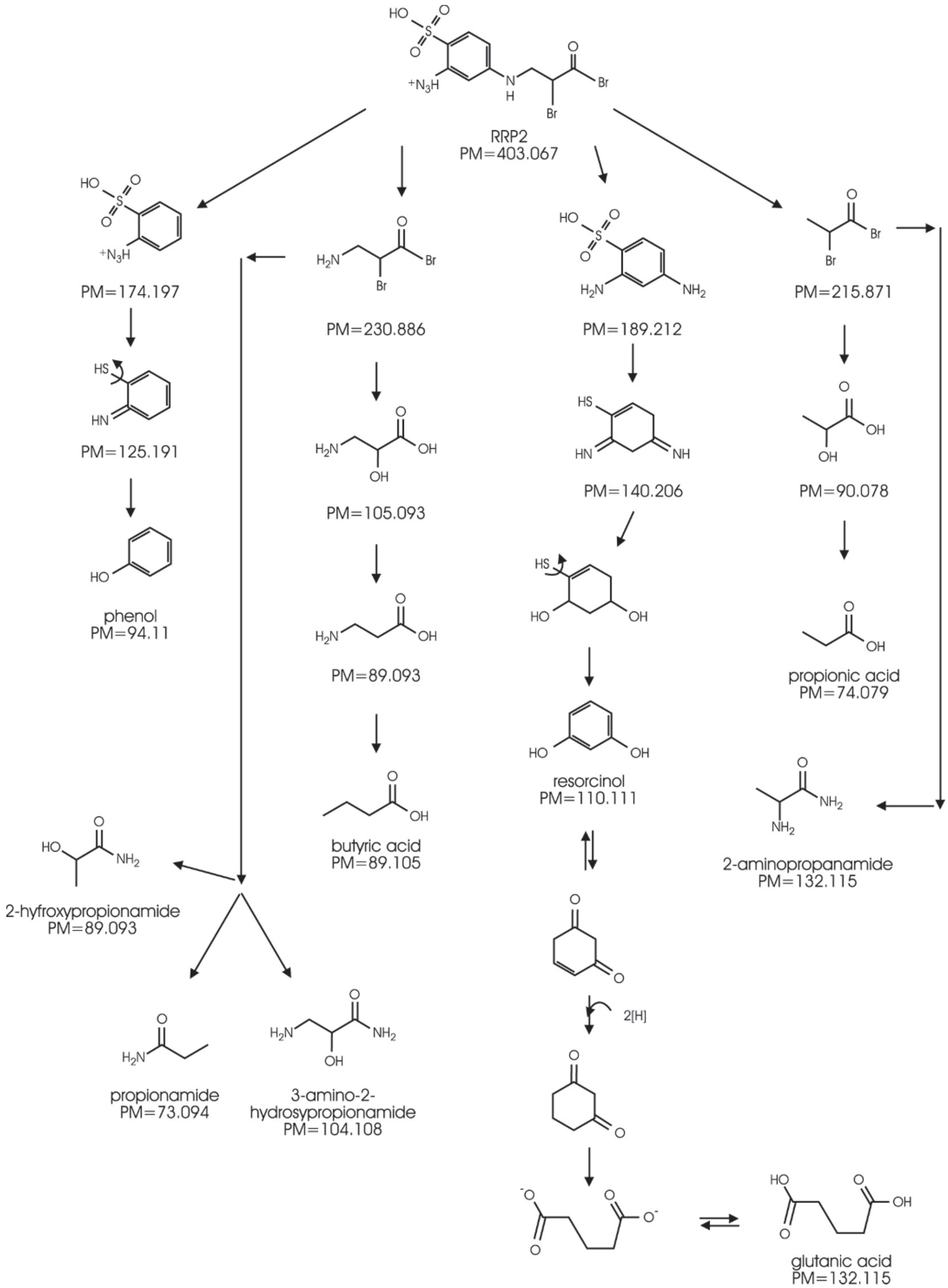


in the reactor. When residence time decreases, the time for the dye to react is less; the same applies to the degradation of reduced products.

22.4.4 Identified Products and Proposed Mechanism

The first step of the mechanism is the reduction of the dye molecule by the breaking of the azo bond bond due to transference of electrons by a redox mediator; this can be a quinone in the surface of acti-

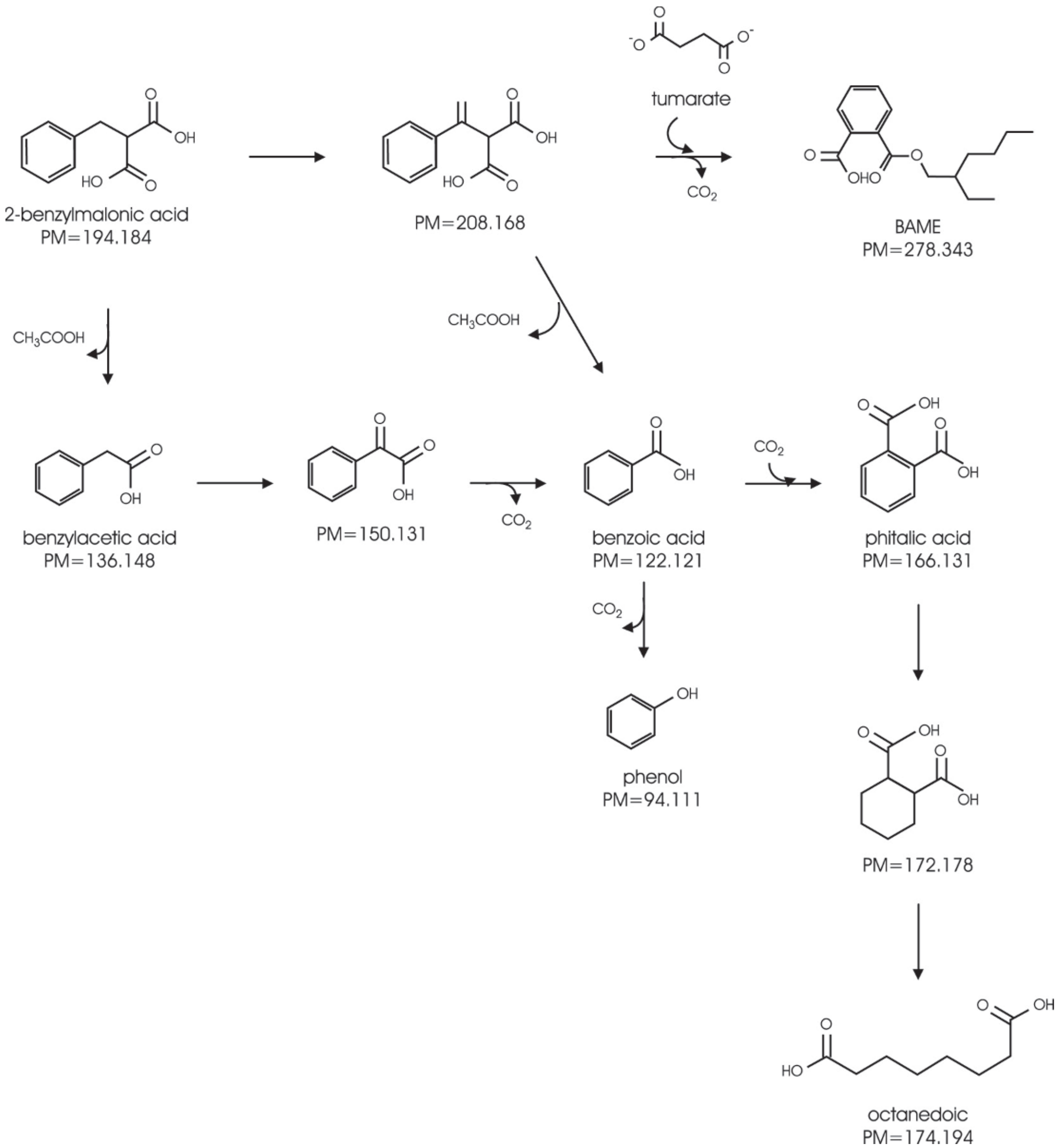
Figure 22.10: Proposed RRP2 degradation route. **Source:** Authors' research results.



vated carbon and/or extracellular enzymes and coenzymes from a primary substrate. At first, the dextrose added to water serves as a carbon source to microorganisms in the reactor and also as source of necessary equivalent reducers in order for the molecule to break from the azo bond. This bond gives the characteristic colour to the molecule, as it breaks, decoloration takes place. Figure 22.5 shows the first step of the mechanism.

Compounds identified in the reactor's effluent varied according to residence time, similar to COD removal. With approximately 50 per cent COD

Figure 22.11: Proposed 2-benzyl-malonic acid degradation route. **Source:** Authors' research results. **Legend:** PM: molecular weight.



removal, the main compounds in the effluent are organic acids and alcohols, as well as an amide and two aromatic compounds as shown in figure 22.6. If residence time decreases or dye concentrations increase, COD removal is reduced, and thus the effluent presents a greater quantity of aromatic compounds; the main ones are shown in figure 22.7.

In an anaerobic environment, degradation of aromatic compounds takes place through hydroxylation and carboxylation, adding molecules of groups -OH, -COOH, CO_2 and even fumarate and succinate, in order for oxidation and the reduction reactions necessary for mineralization of the molecule to take place. This addition of groups and redox reactions is possible due to radical enzymes (Buckel/Golding, 2006) which are induced by the complex substrate in the anaerobic environment inside the reactor.

Based on this and on the results obtained by identification of compounds in the reactor's effluent, some routes are proposed in order to explain degradation (or partial mineralization) of reactive red azo dye 272. Nevertheless, compounds produced by the reduction of the dye can be degraded in various ways, by enzymes or by the metabolism of the cell.

Following the reduction of the dye, the product RRP1 is formed. The degradation route suggested for this particular compound is shown in figures 22.8 and 22.9. In figure 22.10 we can see degradation routes suggested for RRP2. Here, four possible fractions into which the molecule can decompose are shown. Two possible fractions are aromatic sulfonamines.

In these, ammonium groups are displaced by -OH groups through nucleophilic substitution, and sulfonated groups become sulfhydryls before being liberated. After substitutions and reductions, phenol and resorcinol are produced, from which quinone is generated in order to open the bond. Degradation of RRP1 produces benzyl-malonic acid; its proposed route is shown in figure 22.11.

22.4.5 Mathematical Model

The dynamic model for the reactor is based on balances of transport and reaction for the dye flow along the reactor and the bioparticle the reactor and in the bioparticle. Convection, dispersion and diffusion are considered, and dye reduction reactions occur in the fixed bed reactor. The model was designed with the following considerations: a) there is no radial dispersion or it is negligible; b) the dispersion coefficient is constant in each zone; c) the dye can be reversibly adsorbed by particles in the fixed bed (carbon and biomass); d) there is a transference of mass between liquid flowing inside the reactor and bioparticles; and e) average surface speed throughout the fixed bed is constant and equal to $u_L = Q/\varepsilon_L \pi R_i^2$. For the chemical reaction, the order-change kinetic model was taken and is expressed in equation 2. In order to solve the model, the finite difference method was applied, as well as the Runge-Kutta-Felhberg fifth-order method programmed in Fortran. Dimensionless equations of the model are show below, where ω is concentration, ζ the length of the fixed bed, and ξ the radius of the particle (dimensionless).

a) Flow balance for the dye through the reactor:

$$\frac{\partial \omega_L}{\partial \tau} = d_L \frac{\partial^2 \omega_L}{\partial \zeta^2} - \frac{\partial \omega_L}{\partial \zeta} - \beta_m(\omega_L - \omega_b) - \Phi_1^2 Fo_b \omega_L + \Phi_2^2 Fo_b \omega_L (1 - \omega_L) \quad (3)$$

With the following initial and boundary conditions:

$$\begin{array}{ll} \omega_L = 1 & \text{in } \tau = 0 \\ \omega_L = 1 & \text{in } \zeta = 0 \\ \dfrac{\partial \omega_L}{\partial \varsigma} = 0 & \text{in } \zeta = 1 \end{array} \quad (4)$$

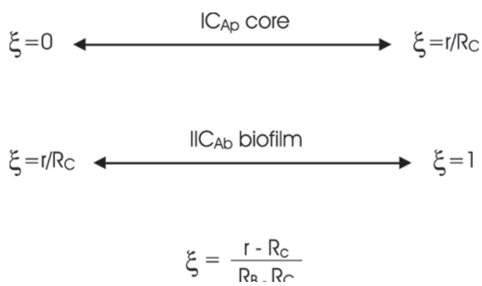
Using the following dimensionless numbers:

$$\omega_L = \frac{C_{AL}}{C_{A0}} \; ; \; \zeta = \frac{Z}{L_f} \; ; \; \tau = \frac{t}{t_{mL}} = \frac{tu_L}{L_f} \; ; \; d_L = \frac{D_L}{u_L L_f} = \frac{1}{Pe_L} \; ; \; \beta_m = \frac{K_m a_{sb} L_f}{u_L} \; \Phi_1^2 = \frac{\delta^2 k_1}{D_{eb}} \; ; \; \Phi_2^2 = \frac{\delta^2 k_2 C_{A0}}{D_{eb}} \; ; \; Fo_b = \frac{D_{eb} L_f}{\delta^2 u_L} \quad (5)$$

b) Balance in the bioparticle:

A parallel model was proposed in order to adimensionalize the two zones as a single particle with a radius between 0 and 1 (figure 22.12):

Figure 22.12: Parallel dimensionless model. **Source:** Authors' research results.



Region I. Activated carbon nucleus:

$$\frac{\partial \omega_p}{\partial \tau} = Fo_p \left(\frac{2}{\xi} \frac{\partial \omega_p}{\partial \xi} + \frac{\partial^2 \omega_p}{\partial \xi^2} \right) \quad (6)$$

Given initial and boundary conditions, expressing field equality at the interface:

$$\begin{array}{ll} \omega_p = 1 & \text{en } \tau \\ \partial \omega_p / \partial \xi = 0 & \text{en } \xi \\ \omega_p = \omega_b & \text{en } \xi \end{array} \quad (7)$$

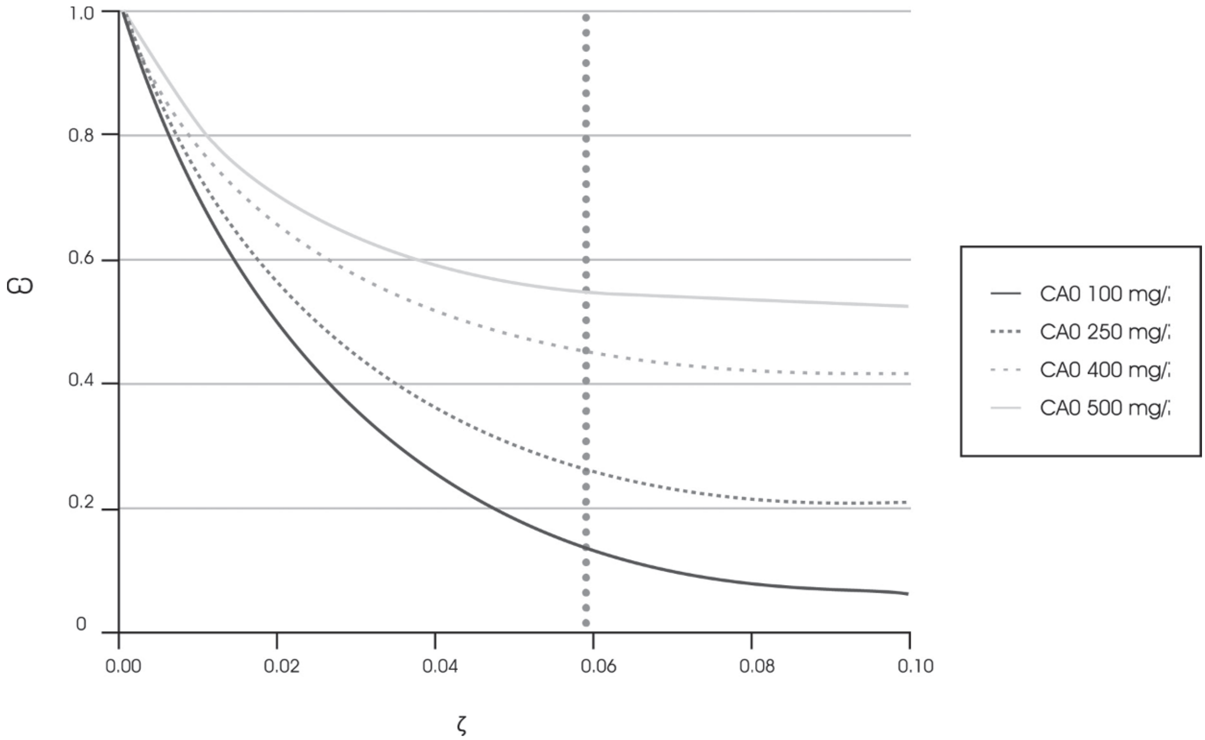
Using dimensionless numbers:

$$\omega_p = \frac{C_{Ap}}{C_{A0}} \; ; \; Fo_p = \frac{D_{ep} L_f}{R_C^2 u_L} \; ; \; \tau = \frac{t}{t_{mL}} = \frac{tu_L}{L_f} \quad (8)$$

Region II. Biofilm, diffusion and reaction:

$$\frac{\partial \omega_b}{\partial \tau} = Fo_b \left[\frac{\partial^2 \omega_b}{\partial \xi^2} + \left(\frac{2}{\xi + \beta} \right) \frac{\partial \omega_b}{\partial \xi} \right] - \Phi_1^2 Fo_b \omega_b + \Phi_2^2 Fo_b \omega_b (\omega_L - \omega_b) \quad (9)$$

Figure 22.13: Predicted concentration profile along the reactor at different initial dye concentrations (C_{A0}). **Source:** Authors' research results.



Given initial and boundary conditions, expressing field equality at the interface and mass transference from the mass particle to the liquid phase:

$$\begin{aligned} &\omega_b = 0 && \text{en } \tau = 0 \\ &\frac{\partial \omega_b}{\partial \xi} = \alpha\, \beta \frac{\partial \omega_p}{\partial \xi} && \text{en } \xi = 0 \\ &\frac{\partial \omega_b}{\partial \xi} + Bi\ \omega_b = Bi\ \omega_L && \text{en } \xi = 1 \end{aligned} \tag{10}$$

Using dimensionless numbers:

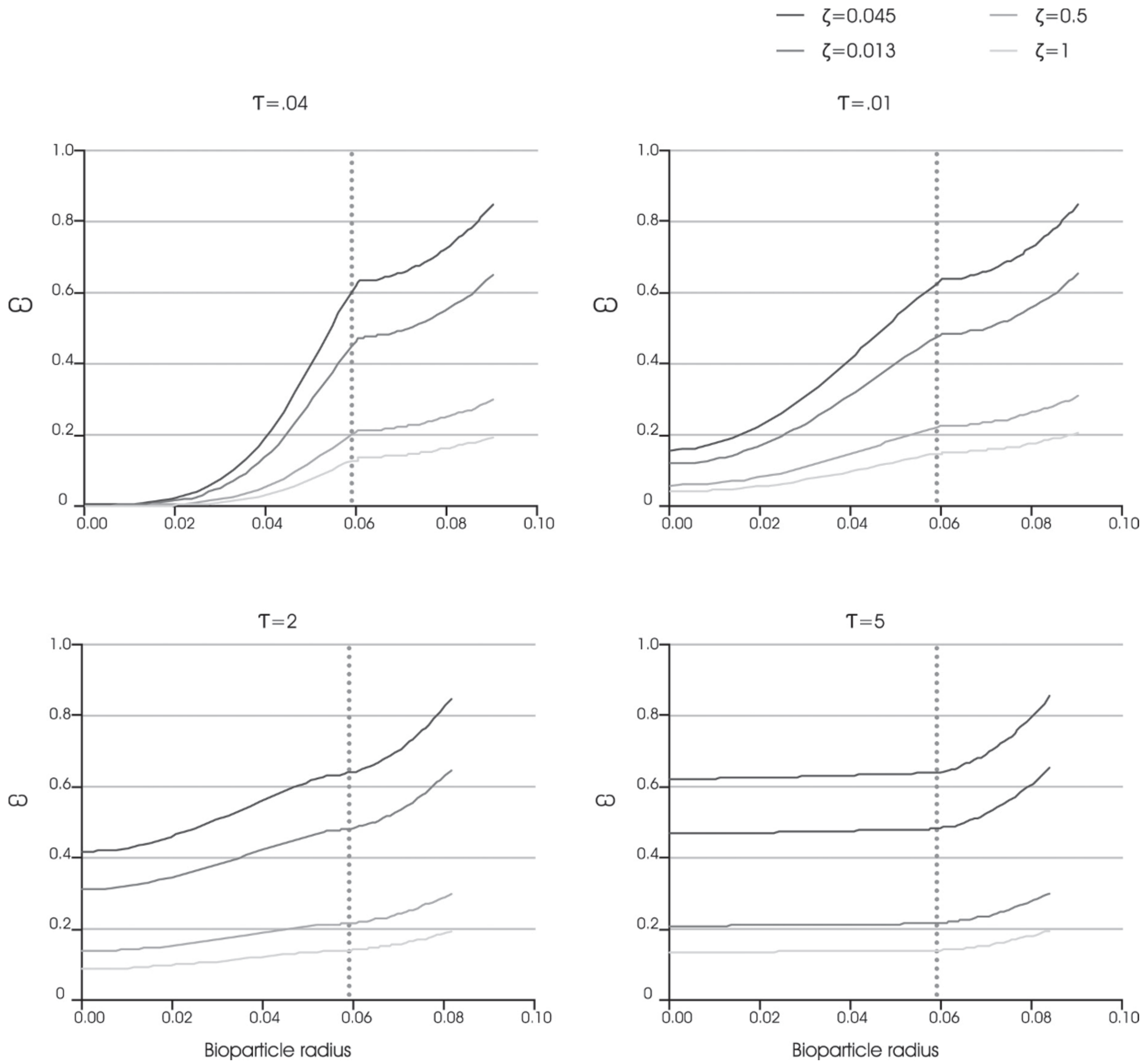
$$\begin{gathered} \omega_b = \frac{C_{Ab}}{C_{A0}} \ ;\ Fo_b = \frac{D_{eb} L_f}{\delta^2 u_L} \ ;\ \tau = \frac{t}{t_{mL}} = \frac{t u_L}{L_f} \ ; \\ \Phi_1^2 = \frac{\delta^2 k_1}{D_{eb}} \ ;\ \Phi_2^2 = \frac{\delta^2 k_2 C_{A0}}{D_{eb}} \ ; \\ Bi = \frac{K_m R_B}{D_{eb}} \ ;\ \alpha = \frac{D_{eb}}{D_{ep}} \ ;\ \beta = \frac{R_C}{R_B - R_C} = \frac{R_C}{\delta} \end{gathered} \tag{11}$$

The model was solved for different initial dye concentrations from 100 and 500 mg/l, and the concentration profile in the bioparticle versus time was analyzed. The predicted concentration profile along the reactor (ζ) can be observed in figure 22.13, i.e., how removal rates change proportionally to dye concentrations. In this figure, we observe that in the first third of the reactor there is a higher degradation reaction which decreases asymptotically throughout the reactor. Also, this effect diminishes as C_{A0} augments.

Figure 22.14 shows the predicted concentration profile in the bioparticle (activated carbon plus the biofilm) for an initial dye concentration of 250 mg/l; a dotted line separates it from AC and the biofilm. Biofilm thickness was 0.03 cm. The profiles showed that bioparticles that are close to the feeding tank (ζ = 0.045) contain higher concentrations of dye than those closer to the reactor's exit (ζ = 1), which have a similar concentration to the effluent. Dye concentration profiles in the bioparticle change according to time (τ) as it saturates and reaches equilibrium; nevertheless, the biofilm region keeps a constant curvy profile indicating the reaction. In the reactor's exit (ζ=1), the profile is more lineal, due that the concentration in the bioparticle becomes uniform as dye concentration is reduced, and there are fewer particles to react.

Predictions coincide with the results obtained experimentally for the continuous operation of the reactor. Thus, the factor with the greatest influence in dye removal rate is initial dye concentration.

Figure 22.14: Predicted concentration profile in the bioparticle at different t (dimensionless time) and z (dimensionless length) in the fixed bed. The radius is in cm. **Source**: Authors' research results.



22.5 Conclusions

Through the proposed anaerobic fixed bed process, an efficient degradation of reactive red azo dye 272 was possible, obtaining up to ~99 per cent of colour removal and 56 per cent of COD, with average residence time from 3 to 5 hours. Activated carbon provides an adequate surface to retain biomass and sustain growth of microorganisms; in addition, it participates in colour reduction as a redox mediator, improving degradation due to active chemical sites on its surface. Also, the used AC absorbed up to 211 mg dye/ACg of reactive red dye.

Dye removal capacity and metabolites (based on COD) increased at pH 5 compared to pH 7; this is because at lower pH levels there is a greater availability of protons to reduce the dye. Thus, the fixed bed reactor operated with AC of pH 5.

Dye reduction follows an order-change kinetic model; in the reaction order changes from the first to the second order, increasing dye concentration. Besides this, as the reaction advances, a decrease in dye concentration relative to time showed an important change, separating dye reduction into two stages: i) abiotic, given adsorption and biosorption, and ii) biotic, where directly related to dye reduction.

Main dye degradation products found in the effluent of the reactor are carboxylic acids, amides, and alcohols. However, dye concentration from 400–500 mg/l or over, and residence time from 3 hours or less, prove insufficient degradation grade and lead to greater amounts of aromatic compounds in the effluent such as phenol and naphthalene, which can be toxic. Despite the numerous aromatic compounds that were found, there were no aromatic amines found in any of the analysed samples, which proves that the process is safe and that dye can be degraded up to a degree that surpasses a simple reduction of the molecule.

Through the proposed mathematical model, the concentration profiles along the reactor and in the bioparticle were predicted. Given the increased initial dye concentration a proportional decrease in removal rate efficiency could be observed. Also, the concentration profiles in the bioparticle demonstrated its saturation point and reflected a reaction zone in the biofilm. These profiles were different according to the reaction zone throughout the reactor, confirming that the reactor has a plug flow behaviour.

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Part IV Social effects, Conflicts and Hydrodiplomacy

23 Water Security, Conflicts and Hydrodiplomacy

Úrsula Oswald Spring

23.1 Introduction[1]

Water is crucial for human survival, productive processes, and the ecosystem. It constitutes between 50 and 90 per cent of the structure of all living organisms. Owing to its appearance from outer space, the Earth is called 'the blue planet', given that 70 per cent of its surface is covered by water, although hydrologic resources only represent 0.07 per cent of its mass and 0.4 per cent of its volume (Oswald, 1999: 41). Likewise, 2.5 per cent of this natural wealth is fresh water, that is to say 35 million cubic kilometres, of which 67.9 per cent is located in glaciers and permanent ice; 0.8 per cent is permafrost; 30.1 per cent corresponds to aquifers; 0.05 per cent is soil humidity; 0.03 per cent wetlands; 0.26 per cent lakes; 0.006 per cent rivers; 0.0003 per cent is biological water; and 0.04 per cent is found in the atmosphere (Shiklomanov et al., 2005).

Of this fresh water, 16.5 *million cubic metres* (Mcm^3) are recycled annually as soil humidity; 2.477 Mcm^3 has frozen over 9,700 years in Greenland, 25 Mcm^3 has frozen in mountains over 1,600 years, and 30 Mcm^3 has become permafrost over a thousand years. Besides this, water is recycled in wetlands over a period of 5 years, for river waters it takes 16 days, and for the atmosphere the cycle is 8 days. These differences in volume and time determine the availability of fresh water for natural and productive processes (Gallopin/Rijsberman, 2000).

Water can be found in three different states: liquid, solid and gas. At the Earth's surface it can travel at different speeds and move laterally or vertically. The hydrological cycle impacts the seasons, it is an important determinant of weather and rainfall, and it is basic to natural ecosystems. The cycle also has important consequences in wider climate processes such as the Niña/Niño (ENSO) effects, which remain insufficiently-studied phenomena (Magaña, 1999) that have greater repercussions than has previously been assumed. Although the hydrological cycle makes water a globally distributed substance, there is water scarcity at different times in different geographical areas.

The complexity of the interrelation between water and the ecosystem, the weather, productive activities, and human needs have meant that water has become a topic on the security agenda[2], and its increasing scarcity and pollution have led to its becoming a conflictual commodity. Following this brief introduction, this chapter analyses water as a crucial aspect of environmental security and establishes its relation to multiple dimensions of security such as food, health, productive or energy security, etc. The third section updates the relationship of water conflicts to other natural resources (climate, soil, biodiversity, jungles and forests), conflicts exacerbated by different social processes (urbanization, the rural context, migration, and hydrometeorological disasters). Through a bi- and multi-lateral hydrodiplomatic model, this section analyses the potential for making consensual agreements to the benefit of all parties involved. In the concluding remarks, water security is linked to the future of the country and its sustainable development following the utilization of its natural, social, political, economic, and cultural capital. This suggests preventive policies of mitigation and adaptation towards climate change, in order to attain processes of resilience that

1 Keywords: hydrodiplomacy, water security and water conflicts.

2 This chapter uses a widened security concept as proposed by the Copenhagen School (Buzan et al., 1998) that expands traditional military and political security to include its economic, social, and environmental dimensions. The security concept is also deepened by supplementing state-centred security with a perspective on human (Brauch, 2005) and gender security (Oswald, 2009). Finally, in order to face the crises and conflicts in different areas of daily life, a sectorialization of security is proposed including water, health, energy and food security (Oswald/Brauch, 2009; Brauch et al., 2008, 2009).

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reduce the vulnerability of marginal social sectors in order to guarantee peaceful resolution of conflicts over the long run.

23.2 Water Security and its Relation to Security in Other Sectors

Water is a crucial element in the analysis of environmental security as it is linked to security in many other sectors. Water maintains environmental services, protects both biological and hydrologic cycles, and the ecosphere (environmental security). It guarantees well-being, leisure, pleasure, and environmental conservation for a multitude of human activities (societal security[3]). It also improves economic security by generating productive and development opportunities (economic security). Besides this, it is a precondition of food security (Oswald, 2009a), allowing farming and transformation of foodstuffs, and enabling human populations to have access to sufficient healthy, nutritious and culturally accepted food. It is for this reason that Allan (2009) refers to *virtual water* when alluding to agricultural products and trade.

Clean water is also indispensable for health security and the overall well-being of the population, as it prevents thirst and dehydration. Nevertheless, water can also cause water-borne and other vector-borne diseases. The relationship between poverty and lack of water or poor quality of water is widespread, both in rural areas where poverty is rampant, as well as in marginal areas of big cities which lack access to clean water, sewage, water management, and sanitation (health security). Greater water security can protect populations from flooding, drought and plagues, given that local authorities act responsibly and evacuate or take preventive measures towards disasters and hunger (human security). Consolidating water security is not linked with traditional agencies of security such as the army, or with military tools used for coercion by physical force. This is precisely why the concept of security has deepened and widened, as it transgresses a narrow Hobbesian outlook and turns its focus on human beings, nature, and societal processes.

According to the Ministerial Declaration of The Hague on Water Security in the 21st Century, adopted in March 2000, the concept was defined as: "ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted; that every person has access to enough safe water at an affordable cost to lead a healthy and productive life and that the vulnerable are protected from the risks of water-related hazards..." (Ministerial Declaration of The Hague on Water Security in the 21st Century, 2000).

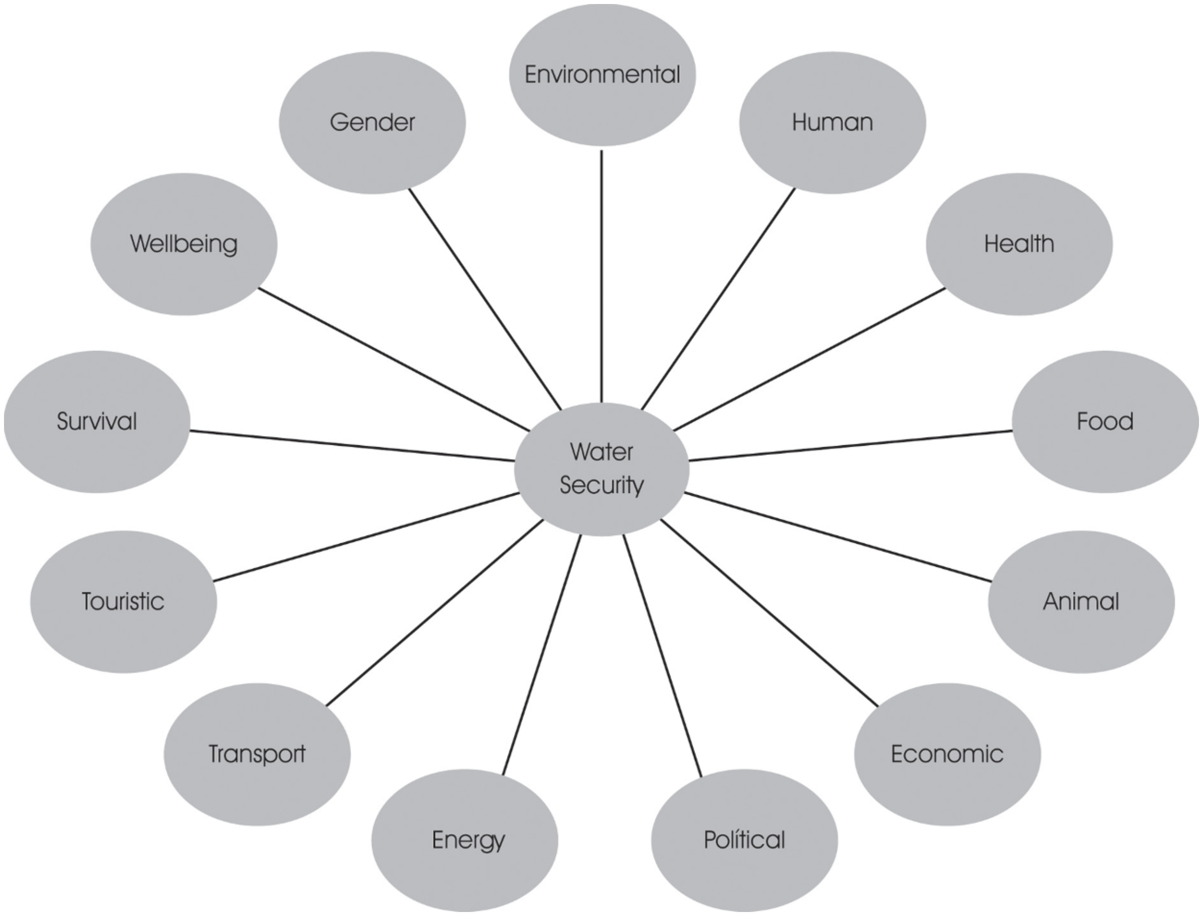
At that event, participants stressed the need to guarantee survival through access to clean water for the most vulnerable (societal security; see figure 23.1); access to food for all human beings (food security); protection of ecosystems (environmental security); sharing transboundary water resources in basins and aquifers (international security); reducing risks associated with extreme hydrometeorological events (human and gender security); overcoming physical and economic stress on water caused by lack of infrastructure by revaluing water (economic security); peacefully solving conflicts concerning increasing scarcity and pollution of the vital fluid as well as promoting water governance (political security); and the protection of human and animal health in the face of water-borne and other vector-borne diseases (health security).

Water can be distinguished in various ways. 'Green water' comes from precipitation and runs off through the ecosystem's soil. It is estimated that the world has 25 million km³ (Mkm³) of green water. It is utilized in the production of up to 60 per cent of seasonal foods, particularly by small farmers and in regions of abundant hydrologic resources. 'Blue water' is to be found in aquifers and is estimated at 33.9 Mkm³ (figure 23.2). Seventy per cent of this water is destined for agriculture in semi-arid, arid and sub-humid regions, generally defined as drylands. Another twenty per cent is consumed by industry and ten per cent is destined for domestic use. Although surface and blue water represent an enormous potential of fresh water, during the last century the population has tripled and water use has increased sixfold. Only in the past twenty years has water consumption doubled, a phenomenon that goes way beyond population growth, which has led to hydrologic stress in regions with low precipitation.

Mexico is one of the countries with significant water stress in many parts of its territory. The annual precipitation is 711 mm on average, approximately 1,522 km³, equivalent to a swimming pool with a depth of one kilometre and the size of Mexico City (figure 23.3; table 23.1). Regionally, the north gets 25 per cent of these rains, whereas 49.6 per cent goes to an area of approximately 27.5 per cent of the coun-

3 The term 'societal security' is used to avoid confusion with 'social security', a term that is commonly used in government programmes. Social security is also a component of societal security.

Figure 23.1: Water security and its links to other sources of security. **Source:** The author.



try's territory in the south-eastern region, in the states of Chiapas, Oaxaca, Campeche, Quintana Roo, Yucatán, Veracruz and Tabasco[4]. For example, in Baja California the average annual rainfall is 199 mm, whereas in Tabasco it is 2,588 mm. Of this rain 72 per cent, equivalent to 1,085 km^3, evaporates. In rivers water run-off accounts for about 412,000 m^3, dams store 180,000 m^3, and lakes and ponds 14,000 m^3; most of this water is used for agriculture. There is also a seasonal element besides these regional discrepancies, namely that 67 per cent of rainfall is concentrated in the period from June to September. Thus, Mexico has a problem of regional and temporal distribution of this vital liquid.

A portion of the rainfall returns to the atmosphere through evapotranspiration (72.5 per cent), another portion runs off through currents (25.4 per cent) or infiltrates and recharges aquifers (2.1 per cent). Considering imports and exports from and to transboundary basins, the country has 458 billion m^3 of renewable fresh water annually (average available natural water capacity). If we divide this by the population, we get an available capacity per capita that has fallen from 17,742 m^3/inhabitant/year in 1950 to 4,427 m^3/inhabitant/year in 2005. This overall value does not directly indicate regional, temporal, and social variations in available water capacity, which in some regions is extremely low.

Table 23.1: Water volume in Mexico (million m^3). **Source:** Author's elaboration based on CONAGUA (2009).

Rainfall	1,522,000
Rivers	412,000
Dams	180,000
Lakes and ponds	14,000

4 While water availability per capita in Baja California is 1,336 m^3/inhabitant, in Chiapas it is 24,674 m^3/inhabitant (Carabias/Landa, 2005).

Figure 23.2: Green and Blue Water Global Flow. **Source**: UNEP (2007).

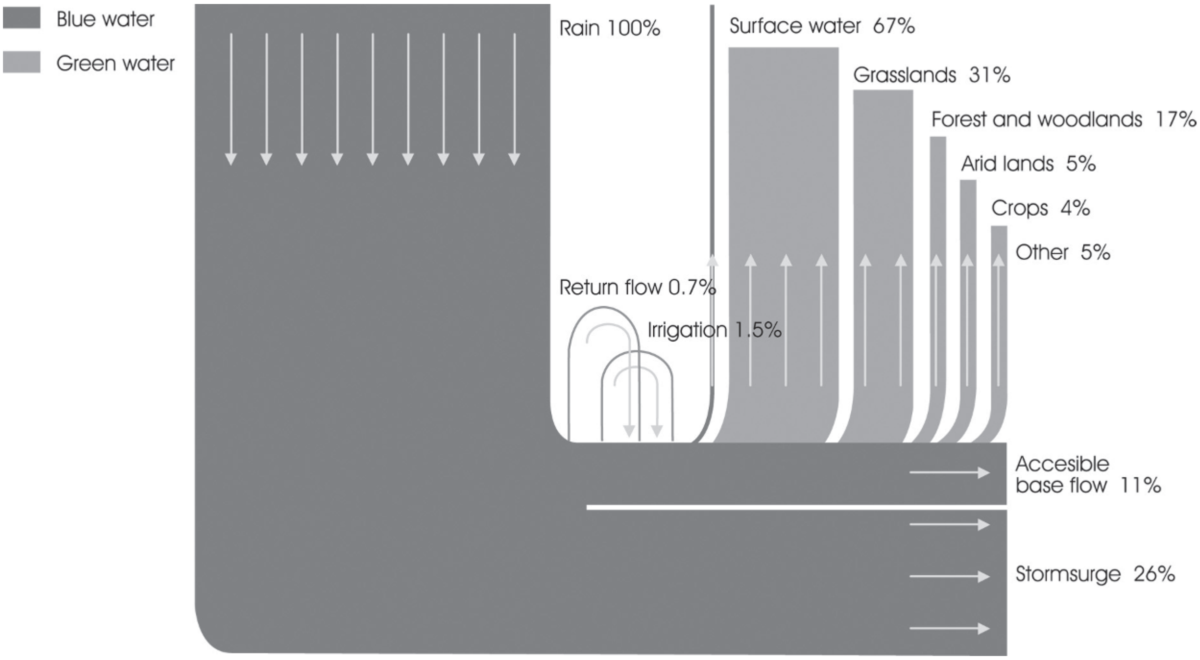


Figure 23.3: Annual Rainfall in Mexico. **Source:** CONAGUA (2009).

Mexico has 837 hydrographic basins with size variations and distinct characteristics. It also has 42 main rivers that flow principally into the Atlantic and Pacific Oceans, and inland to smaller rivers, lakes, and dams. The use and management of surface and groundwater is divided into thirteen Hydrological and Administrative Regions. Out of the 653 aquifers 104 are over-exploited[5], even though, given its quality and potential, and compared to surface water, groundwater is a strategic resource for the country's development. The situation has worsened given that 93 per cent of extracted groundwater comes from only 282 aquifers, which puts tremendous pressure on them. On average, during the past decade, 77 per cent of water was destined for agricultural use with 6.3 million hectares of irrigated land, for which between 40 to 60 per cent of water was extracted from aquifers and with an overall water use efficiency estimated at 33 per cent.

Municipal and domestic consumption accounts for 13 per cent (a little higher than the world average), whereas industry extracts 10 per cent, according to concessions registers. Given its high pollution, water quality is poor, and international evaluations put Mexico in 106th place out of 122 countries (OECD, 2009). Only 27.6 per cent of wastewater is treated and treatment plants often lack maintenance or have stopped working. Furthermore, 22.9 million inhabitants – especially in marginal areas in the south-east – lack piped water and 37.9 million have no sewage.

23.3 Water Conflicts and Hydrodiplomacy

According to the *Organization for Economic Co-operation and Development* (OECD, 2009), 880 mil-

5 Out of Mexico's 653 aquifers, in 1975 only 68 were overused; in 2007, this figure rose to 101. In 2009, there were 104 over-exploited aquifers in Mexico.

lion inhabitants worldwide lack access to drinking water, a figure that may increase to 3.9 billion by 2030. Another 2.5 billion lack access to proper sanitation, and according to the OECD 2.6 billion people, mainly in Asia and Africa, lack access to both water and sanitation, increasing the risk of diarrhoea and other water-borne diseases, with fatal consequences for children. "An estimated 425 million children under 18 still do not have access to an improved water supply, and over 980 million do not have access to adequate sanitation", according to UNICEF's executive director Ann Veneman. Lack of water is particularly acute in sub-Saharan Africa, with 11 per cent of the world population, and a third of the people lacking this vital resource.

The situation in Latin America and the Caribbean has improved; access to potable water increased from 83 per cent in 1990 to 91 per cent in 2004, whilst sanitation rose from 68 to 77 per cent in the same period. However, more than 100 million people still lack potable water and basic sanitation services. This has intra-regional variances; 86 per cent of urban residents have access to improved sanitation facilities whereas 51 per cent of inhabitants of rural areas lack these services.

In Mexico, according to CONAGUA (2009), 91 per cent urban residents have access to basic sanitation, contrasted with only 41 per cent of the rural population. Advances over the past years have reduced mortality rates in children under 5 years of age by 43 per cent; from 54 infant deaths per thousand in 1999, by 2004 the rate had fallen to 31. Future water scenarios in Mexico need to consider population growth and its concentration in urban zones. CONAPO (2009) estimates that between 2007 and 2030 the population of Mexico will increase by 14.9 million people. Also, 82 per cent of this population will settle in cities by the year 2030, although growth will differ in the various hydrological regions, further impacting the unequal regional distribution of water per capita. Some of Mexico's hydrological and administrative regions will have a per capita water availability lower than 1,000 m^3/inhabitant/year; this represents a condition of high scarcity.

Mexico cannot rely on its groundwater because over-exploitation of aquifers has led to the depletion of the phreatic level, subsidence, and the need to dig deeper wells. Finally, the situation of Mexico is aggravated by chronic economic stress, especially as the government's expenditure favours administrative expenses, the servicing of internal and external debts, paying for FOBAPROA (bank rescue), and increasingly also military security and combating organized crime instead of investing in basic infrastructure and maintenance.

23.3.1 Conflicting Interrelationship of Water and other Natural Resources and Social Processes

In order to avoid conflicts relating to water shortages, water demand has to be reduced through integrated management of forests, land, river basins, and aquifers. This includes reforestation, and saving, reusing and recycling water in houses, industries, and agriculture. Also, efficiency must improve in order to overcome leaks, and water needs to be treated so it can be reused in agriculture, parks, and gardens. These practices may reduce water stress. Figure 23.4 maps the complex interrelation between natural water supply and its social demand, as well as potential sources of water-related conflicts.

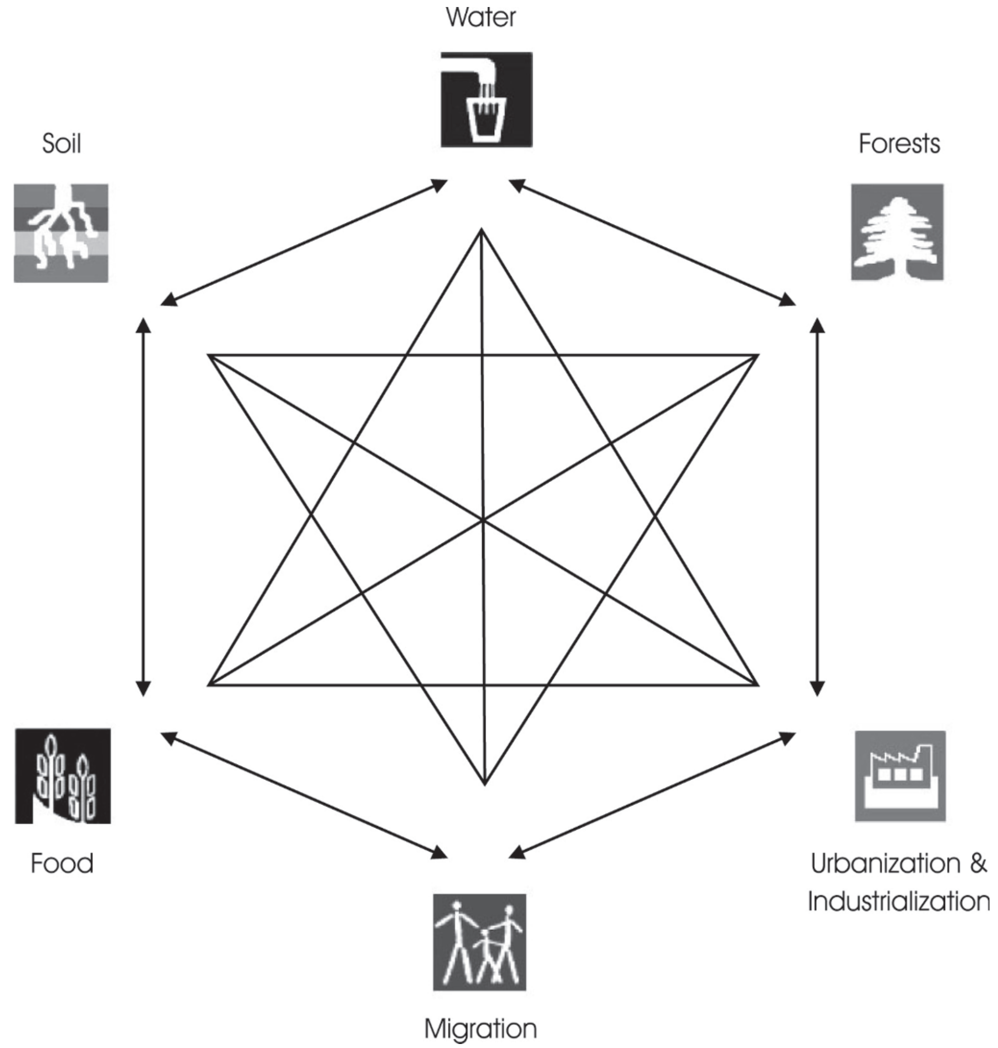
23.3.1.1 Weather and Water

The acute processes of change in land use from forests for urban and agricultural purposes, together with the destruction of forests, jungles and mangrove swamps, have exacerbated weather events, making them more extreme. "North America, with its predominantly meridional orographic structures, constitutes the right setting in which masses of cold air propagate southwards towards Mexico, Central America, and the Caribbean" (Magaña et al., 2004: 35). Although this is a natural phenomenon of the weather system, and has always existed, it seems that both the frequency and intensity of natural disasters have increased, for example during 1997/1998 and from the year 2004 onwards. Worst have been the hurricanes and floods in 2005, 2007 and beyond; these caused many human and material losses as well as conflicts in the south-east of Mexico. At the same time, droughts in arid and semi-arid regions in the north and centre have caused soils to deteriorate, reducing natural fertility and agricultural yields, generating mass migrations from rural lands, and leading to the abandonment of entire communities. The year 2009 marked the worse drought for the past seventy years.

23.3.1.2 Land and Water

Mexico is severely affected by processes of desertification, land degradation, and soil fertility loss. According to SEMARNAT (2006), 93 million hectares, equivalent to 47 per cent of the overall territory, have

Figure 23.4: Interrelationship between water supply, human demand, and potential conflicts. **Source:** Oswald Spring/Davis Mazlum, in Davis Mazlum (2004: 17).



experienced some degree of desertification. According to RIOD-MEX (2008) this process has affected 120 million hectares of which 93 per cent is the result of bad land management. The main causes are loss of fertility (18 per cent), water erosion (12 per cent), and salinization (8 per cent; figure 23.5).

CONAFOR (2009) establishes a link between water, land degradation and poverty, where poor soils and lack of productivity trigger malnutrition, unemployment, and misery. This panorama is aggravated by water scarcity and severe pollution (Biswas et al., 2007). Following acute processes of urbanization, deforestation, and destruction of ecosystems, 837 hydrological basins with different characteristics are now polluted, including the 42 main rivers in the country. Something similar occurs with the 653 aquifers, 104 of which are over-exploited, and seven in particular in Mexico City are showing severe depletion processes.

23.3.1.3 Biodiversity, Jungles, Forests, and Water

According to CONABIO (2009), given its geographical location, Mexico has a very rich diversity of ecosystems, ranging from high mountains with arctic ecosystems to deep-sea marine ecosystems, including temperate, subtropical, tropical, forest, lagoon, coastal, coral, and desert systems. The fundamental ecological processes of ecosystems such as the water cycle, the biogeochemical nutrient cycle, and the energy cycle interrelate with community dynamics. They generate environmental services basic to humans such as pure air in the atmosphere. They regulate the weather and precipitation patterns, purifying and improving water quality. They control hydrological cycles, including natural protection from disasters such as floods and droughts. They defend coastal zones with coral reef systems, sand dunes and mangroves from hurricanes and waves, and they keep soils fertile through micro-organisms and biological combat in the face of parasites, fungi and viruses, as well as vector-borne diseases. Additionally, these ecological processes account for crop pollination, providing terrestrial and marine foodstuffs with a genetic diversity that has been used by human groups throughout the past ten thousand years to domesticate animals and to develop crops, medicine and industrial products. All these factors have contributed to the development of the most important civilizations throughout the world.

These natural processes have been severely affected by productive activities. According to the GEO-4 Report (UNEP, 2007), the normal activities of a human being affect 21.9 hectares, contrasted with the biological capacity of the Earth at 15.7 hectares on average. Besides this, only 16 per cent of solid waste is managed efficiently, and waste generation per capita has increased enormously during the past two decades, given the changes in consumption patterns, mainly in developing countries.

The relationship between anthropogenic and natural processes has changed the composition and structure of ecosystems, perturbing times and cycles. Overall, having less water and sometimes having great amounts of water over short periods of time, the increases in temperature, deforestation, and indiscriminate hunting have all affected biodiversity in Mexico and on the planet. Erosion, land degradation, and deforestation have reduced natural soil fertility, while chemical fertilization has contaminated soils, surface water, and groundwater.

Small farmers, without any government support and without any recognition of their contribution of environmental services to cities, face the challenge of survival (Oswald, 1991). In Mexico, between 300,000 and 400,000 people leave the rural areas annually in their struggle to improve their quality of life in bigger cities, or they hope to cross the border to the USA, with all the dangers associated with illegal crossing of militarized borders, controlled on the Mexican side by the organized crime.

23.3.1.4 Water and Urban Processes

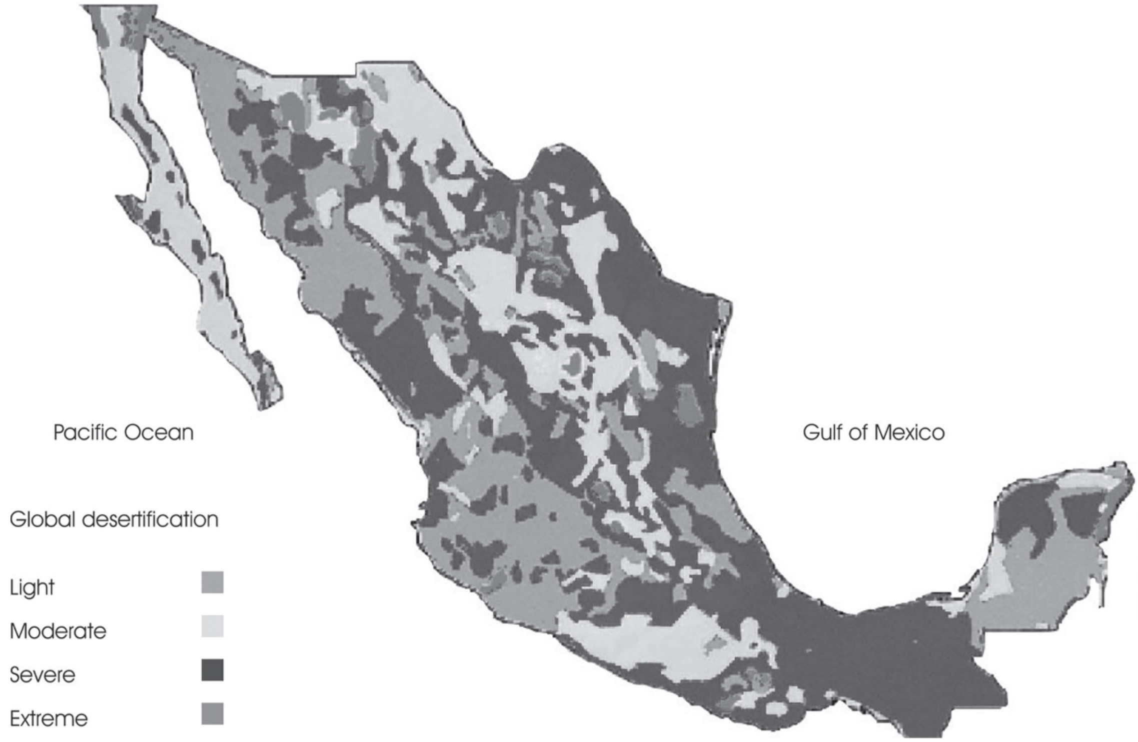
Urbanization processes in Mexico have experienced different phases, although they have always been linked to failed agricultural policies. Between 1950 and 1970 the transfer of rural capital in favour of urban and industrial development led to a mass migration from rural areas to Mexico City, and later to Guadalajara and Monterrey. Poor peasants settled in shanty towns surrounding big cities (figure 23.6 and figure 25.7). Between 1970 and 1990, rural-urban migration peaked following a policy of import substitution, dependency on oil, and cheap agricultural prices, a rural policy based on the green revolution movement, promoting competitive advantage, multiple economic crises, and hindering rural development. Growing slums and high air pollution challenged governmental authorities in Mexico City.

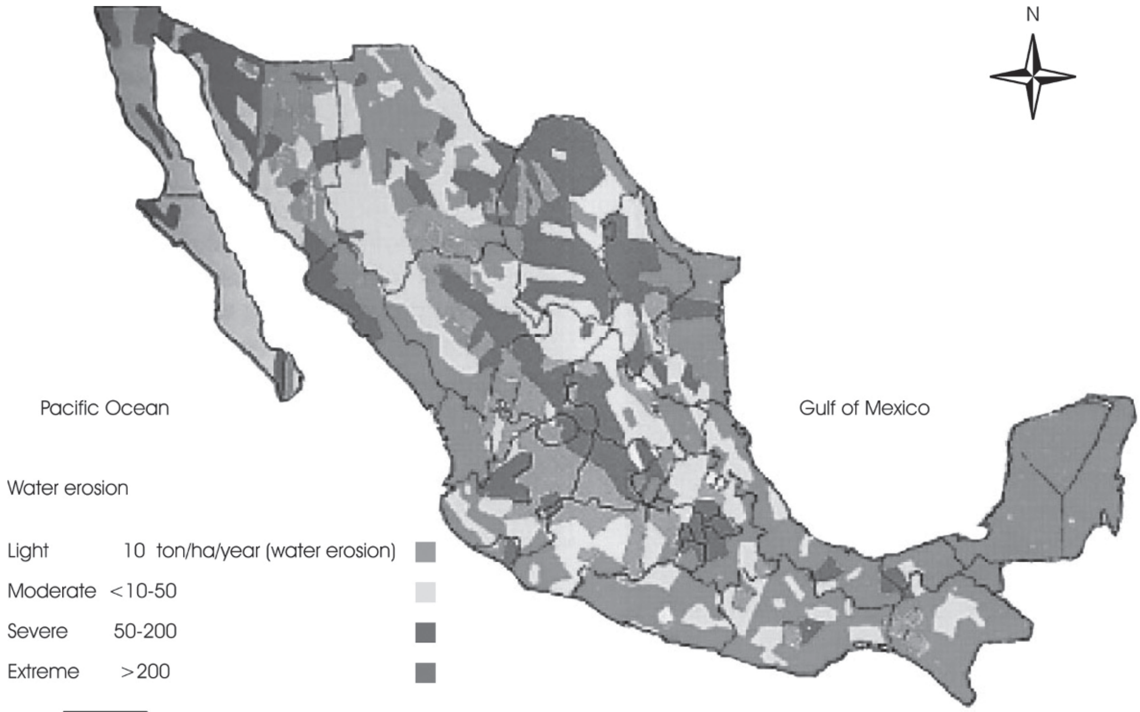
Between 1995 and 2005 a new path was sought in economic globalization with the integration of Mexico into the world market through various free trade agreements. The *North American Free Trade Agreement* (NAFTA) allowed the import of food crops at cheaper prices, generating a new wave of migration, especially to the USA. This phenomenon was accelerated due to water scarcity, soil erosion, the destruction of hydrologic infrastructure, and the general abandonment of subsistence agriculture by the government in favour of big agribusinesses and competitive advantage.

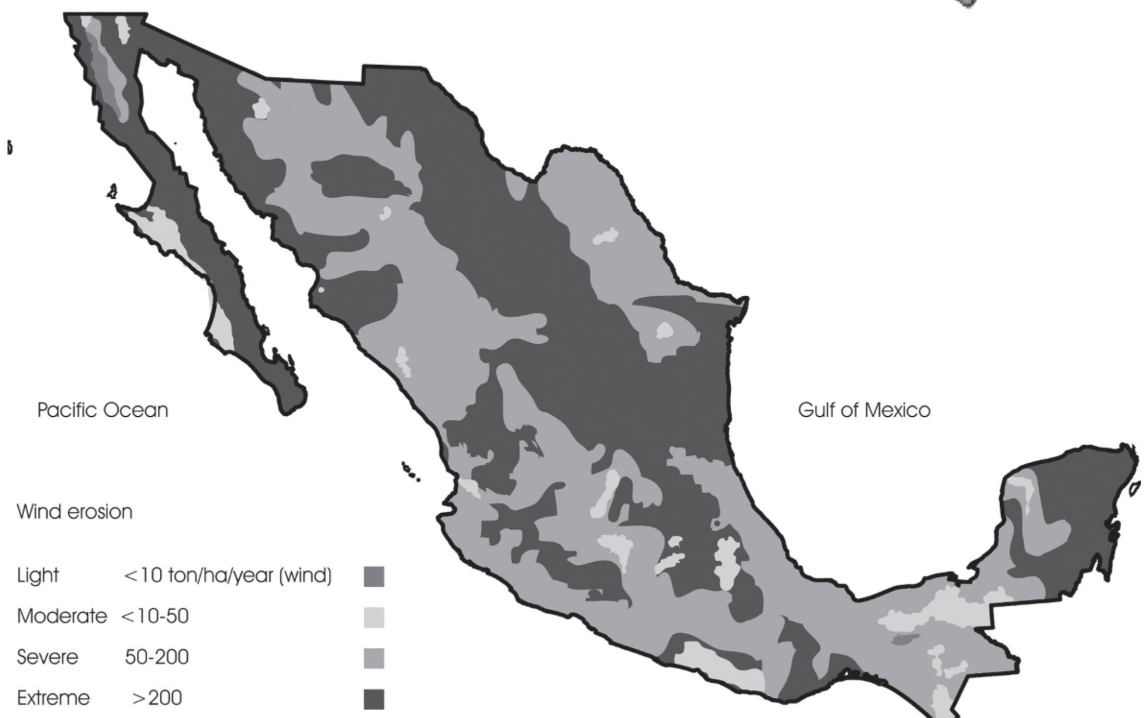
Since 2005, natural disasters have been more frequent and severe, together with processes of desertification, drought, land degradation, over-exploitation of aquifers, and low agricultural prices. However, the sudden increases in cereal prices in 2007 due to speculation and to a greater demand for grain for the production of biofuels in the USA have contributed to massive protests and hunger riots during 2008, and also to new waves of illegal international migrations, but this time focused on the medium-sized cities in the USA (figure 23.8). Facing increased vigilance at the frontier, and an unparalleled economic and environmental crisis, many migrants linked up with organized crime in order to cross the border, as well as using the most dangerous route through the Arizona desert.

This initial rural-urban migration with chaotic urban development and a recent and unparalleled international migration have resulted from a failed rural policy where rural capital was transferred to a shrinking urban elite connected with an inefficient and corrupt government, exacerbated by the signing of NAFTA in 1993. The transfer of power in Mexico from one-party rule to the opposition in 2000 increased poverty, while public expenditure was duplicated, and oil revenues between 2000 and 2006 were squandered because of the high oil prices in that period. Since 2007, with the prospect of lower oil

Figure 23.5: Causes of land degradation in Mexico, a) desertification, b) salinization, c) water erosion, d) wind erosion.
Source: SEMARNAT, INE (2005) based on CONAZA (1994).







prices, public spending further increased threefold to 2009, compared with the year 2000. This situation is further aggravated by the global financial crisis.

In terms of water, over-exploitation of the seven aquifers in the Central Valley of Mexico has induced subsidence. Recently there have been permanent cuts in water supply, and bringing the water from the Lerma-Cutzamala basin to Mexico City results in high energy pumping costs and is destroying indigenous zones in the state of Mexico and Michoacán. The water supply in this megacity is the result of several contradictory policies due to the building of a new sewage water collector in 2010, and to the lack of infrastructure for rain water infiltration, sanitation, recycling and water reuse in parks and productive processes. In the valley of Mexico these developments have increased water scarcity, triggered the over-exploitation of aquifers, and increased dependence on external sources. This further depletes aquifers and prevents their recharge, and this has caused the collapse of buildings and streets through subsidence.

23.3.1.5 Water and Rural Processes

Natural and social processes have put pressure on rural production during the last half-century. In the first decade of the 21st century, about 1.78 million peasants have migrated, especially towards North America. Two out of three peasants in rural areas live below the poverty line; their average age is more than 55 years, and there is an accelerated process of feminization of agricultural production caused by migration. Low prices for agricultural products have been the result of US subsidies, and indiscriminate imports of basic foodstuffs were instrumental in Mexico's losing its food security. From 1994, when Mexico joined NAFTA, to 2008, maize imports increased from 2.5 to 6.148 million tons (mt); for basic grains the imports rose from 8.7 to 18.7 mt. In 2005, one decade after joining NAFTA, Mexico imported 95 per cent of soya, 58.6 per cent of rice, 49 per cent of wheat, 25 per cent of maize and 40 per cent of meat. Food imports during the first ten years of NAFTA (1994–2003) amounted to 78 billion US dollars (Banco de México, 2004; INEGI, 2004). If part of these financial resources had been used to stimulate the agricultural sector, the agricultural crisis could have been avoided, businesses could have benefitted in Mexico, the internal labour market could have been stabilized, and poverty in rural areas could have been overcome, increasing human and food security and improving environmental services.

Agriculture uses 77 per cent of the ground and surface water, and occupies 70 per cent of the territory. A total of 112 million hectares are used for livestock that consumes about two per cent of this water. Only 23 million hectares are cultivated, of which 90 per cent in the northern arid areas are irrigated.

As a first stage, since the 1990s the federal government has transferred 3.39 million hectares of irrigated land to 547,000 users represented by 454 water users' associations and ten limited-liability societies that manage the irrigation districts. This policy covers 98 per cent of all irrigation lands. The main goal of the federal government has been to charge fees for water services with which almost 72 per cent of the maintenance costs of irrigation infrastructure are covered. At the same time, CONAGUA has supported efforts to enhance the efficiency of irrigation, e.g. through drop systems, micro-sprinkler irrigation, micro-irrigation tunnels, etc., and to develop a large-scale water infrastructure.

In response to global environmental change and extreme hydrometeorological events, the federal and state governments should intensify the ecological planning of the land and of coastal areas through the conservation of agrobiodiversity, and the recuperation and conservation of soils and waters. Furthermore, in response to climate change, mitigation and adaptation strategies are needed.

The agricultural sector is also the greatest pollutant of natural resources due to an extensive use of pesticides that affect surface water and degrade aquifers, spreading pollution in all parts of the country. Besides reducing water quality and affecting the soil's natural fertility, leaching pesticides also cause water, flora, fauna as well as coastal and river basins to deteriorate. Thus, important initiatives have been launched to substitute pesticides with biofertilizers that combat and control plagues and diseases naturally, as well as to reintroduce organic farming with crop rotation, green production, compost and mixed agriculture, i.e. turning to a model of sustainable agriculture. Biodigesters not only clean water from sewage in rural areas, but they also generate biogas and biofertilizers. With an integrated rural development strategy, the exodus of Mexican farmers could be countered.

23.3.1.6 Migration and Water

Rural-urban migration is concentrated mainly in the *Conurbation Zone in the Valley of Mexico* (CZVM), including Mexico City, 27 municipalities in the state of Mexico and recently also some municipalities in the state of Hidalgo (figures 23.6, 23.7). At the beginning of the 20th century, human population density in the capital city was 32.2 people/km^2, increasing to 2450.7 people/km^2, compared with the national average of 53 people/km^2. Between 1970 and 1980, about 3.25 million people migrated to the capital city. This process was not homogenous and there are also important differences in the population dynamics within the CZVM. Some areas in the state of Mexico and Azcapotzalco grew by 13.6 per cent between 1950 and 1980 whilst some central parts of Mexico City grew by 3.3 per cent. Urbanization processes are not limited to the CZVM. Mexico currently has 55 metropolitan zones with a population of 55 million inhabitants; they

Figure 23.6: Population growth in Mexico City. **Source:** INEGI (1960-1990).

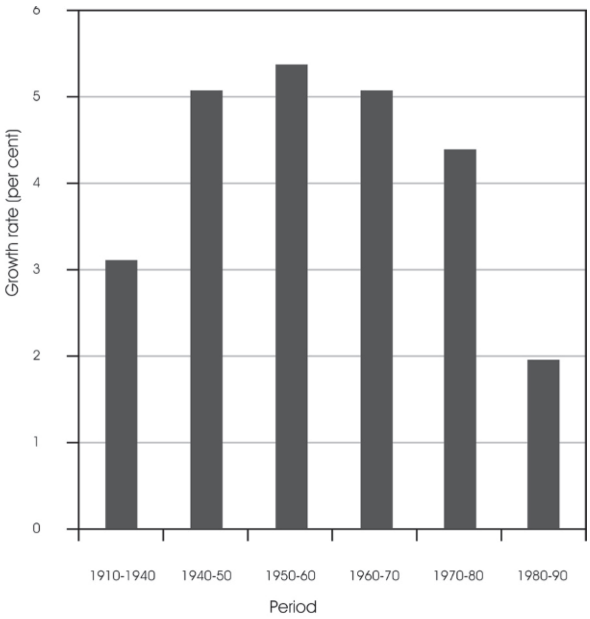


Figure 23.7: Population in Mexico City and in the states of Mexico and Hidalgo**. Source:** INEGI (1990).

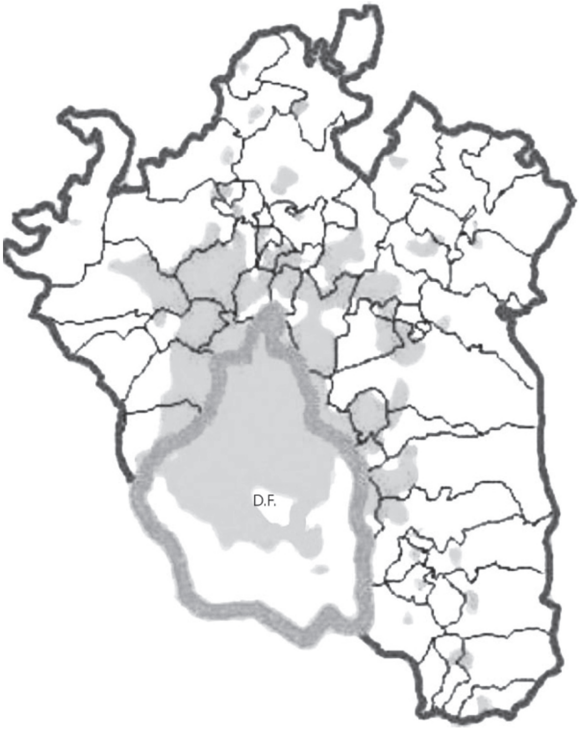
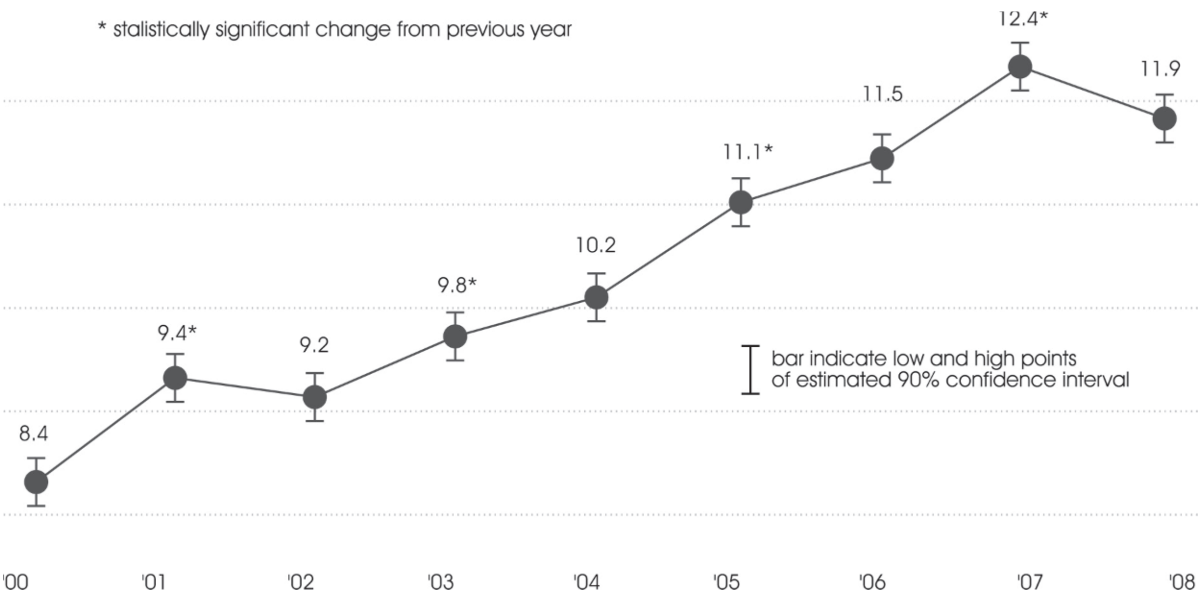


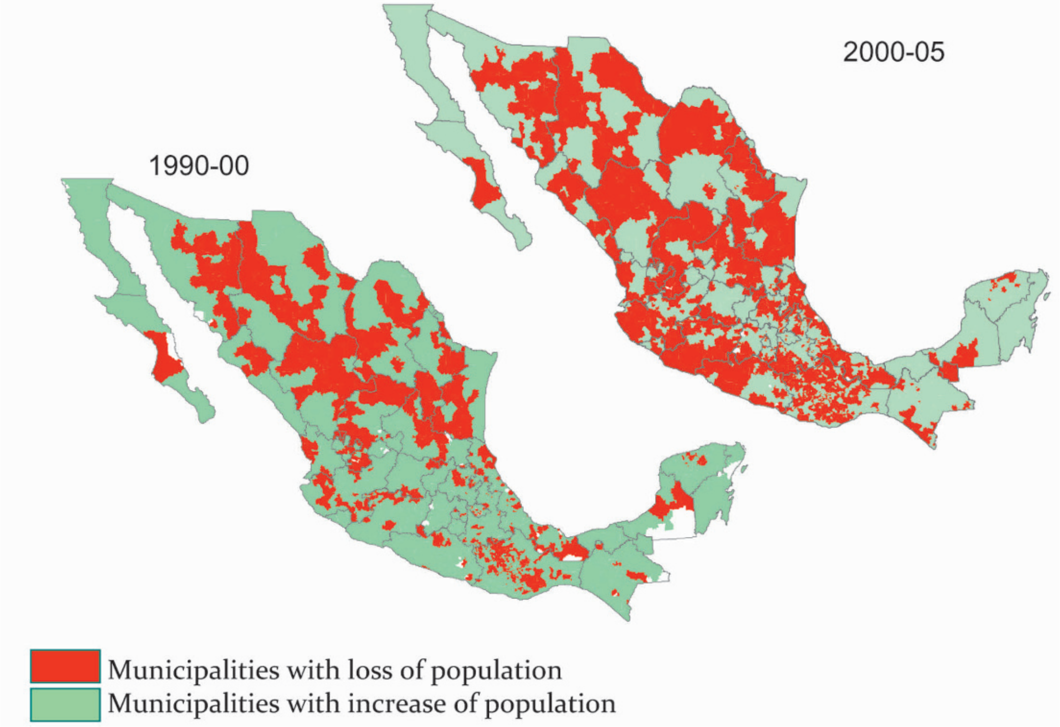
Figure 23.8: Illegal immigrants in the USA, 2000-2008. **Source:** PEW (2009).



represent half the country's total population. They demand potable water services and produce wastewater and garbage. In dealing with the water supply crisis in the metropolitan zones, it is important to improve the management of drinking water, reduce leaks in pipes, recycle water for irrigation in gardens and parks, reduce consumption, and collect rainwater.

Migration towards the USA (figure 23.8) has been an escape route for thousands of young people and those whose lands have stopped producing profitable agricultural crops. According to the *International*

Figure 23.9: Loss of population in drylands. **Source:** Designed by F. Lozano based on INEGI (1990, 2000, 2005).



Migration Outlook (OECD/SOPEMI, 2008: 262–263): "unauthorized migration from Mexico towards the USA is estimated at around 315 thousand people/year, to which 6.57 million illegal Mexican residents already living in the USA must be added". The maps of population loss especially in rural areas show that since 1990 migrants usually come from municipalities affected by prolonged drought, desertification, and loss of natural soil fertility (figure 23.9).

Migration has always been a partial solution to problems of lack of water, food, and human security. Usually, women, children, and older people stay behind in charge of the parcel of land or live in shanty towns awaiting remittances. Using survival strategies (Oswald, 1991, 2008), women have become de facto household heads, economically supporting their children and sometimes even the extended family. In addition, they often have to pay the cost of their husband's illegal crossing to the USA. These adverse conditions are exacerbated by low salaries in rural areas, lack of government support, and the lack of private ownership or entitlement to communal land. As can be seen in figures 23.8 and 23.9, as the rural crisis has deepened, international migration has increased and remittances reached US$ 25.15 billion in 2008 and dropped in 2010 by 15 per cent to US$ 21.271 billion. Given tighter border controls, but especially due to the present economic crisis, in 2009, 393,289 Mexican immigrants have been expulsed (Pew Hispanic Center). This has put an enormous pressure on the Mexican labour market, where even before the crisis half of the population worked in the informal sector.

Linking natural (air, climate, water, biodiversity and soil) and anthropogenic factors (urban and rural systems, migration), BANAMEX stated that in the year 2004 alone, 38 per cent of the available jobs in agriculture were lost, leading to rural-urban and international migration, where tighter and more militarized border controls have increased death rates, thus reducing human security. However, given that the economic recovery in the USA needs additional labour, illegal immigration is 'tolerated' as a lesser evil, although the Mexican government has been unable to generate rural employment with a decent income.[6]

According to National Institute of Geography and Statistics (INEGI in Spanish), remittances reached more than 14 billion US$ in the year 2004; the Inter-American Development Bank estimated 16.613 billion (IDB/BID, 2005), which helped mitigate rural poverty and and reached a peak in 2008 of US$ 25.15 billion, making a total of 1,100 billion US$ over the past decade (IDB/BID, 2009). Following the global economic crisis in 2008, remittances fell by 13 per cent and many repatriated immigrants put further pressure on the tense national labour market in Mexico. Data from the last Household Income and Expenditure Survey (INEGI, 2009) reported an increase of 5 million poor people, of which 3 million face food poverty as a result of a failed policy, with rising prices of basic grains and mounting unemployment.

Neo-liberal economic policies, which have been reactive in the social area and laissez-faire in environmental terms, have severely affected food and health security. Furthermore, Mexico is a country severely affected by natural disasters exacerbated by a lack of prevention, mitigation, and coping strategies. Land erosion, risky urban settings, deteriorating infrastructure and the abandonment of small scale agriculture have impacted on natural disasters (table 23.2). Mexico's more than 11,000 kilometres of coastline are highly vulnerable to various hurricanes both on the Atlantic and Pacific, as well as to rising sea levels. According to specialists on cyclones, the coast in the Gulf of Mexico is particularly vulnerable to these phenomena and they require prevention, especially during Niño years (Magaño, 1999). These are the zones prone to flooding and from which people will have to be evacuated in the future due to rising sea levels. Thus, in order to understand climate change in the region it is necessary to analyse the interaction of the atmosphere and oceans, orographic variables, land use, ground cover, city zones, and human settlements, as well as their productive activities.

In synthesis, the federal and state policies of environmental neglect, deforestation, land use change for agricultural, urban and tourist use, and the chaotic development of big cities, have negatively affected water resources, soils and the landscape. Due to climatic factors, water availability has become even scarcer in arid regions. The pressure on the water and on land

Table 23.2: Natural risk in Mexico: Volcanoes, floods, hurricanes, earthquakes, landslides. **Source**: Developed by the author, based on SEGOB-CENAPRED (2009).

Degree of Risk	People (millions)	Percentage of affected population
Very high	32.1	28.6
High	12.4	11.0
Regular	27.2	24.2
Low	16.1	14.3
Very Low	24.5	21.9

has become more severe. Between 1992 and 2003 the Secretariat of Agrarian Reform has dealt with 631,314 agrarian conflicts; most of them were also related to water conflicts. Since the Constitution was reformed, the amendments of article 27 that offered the possibility to sell or rent individually the common land, increasing substantially land conflicts.[7]

In all Mexican states, water and land have become a serious challenge for governance. Given this conflicting situation, which was further exacerbated by public insecurity and the economic crisis, the challenge has been to adopt mechanisms of negotiation that can offer solutions for sharing scarce resources sustainably, and to administer them among all stakeholders. This necessary policy response links the federal, state and municipal governments, economic actors and organized civil society to promote political security in a democratic framework that offers all Mexicans the opportunity to live in dignity, to be better protected from extreme hydrometeorological threats, to have access to sufficient clean water to de-

6 According to the National Labour Census (last term of 2004), 63.5 per cent of the working population – namely 26.7 million workers – had no social security protection. This figure had increased by 2.749 million contrasted with the same period of the previous year and further rose in 2009 due to the financial crisis. At least 31 per cent of the economically active population – 10.8 million people – worked in the informal sector of the economy during the last term of 2003; this figure increased to 11.2 million people in 2004. The authorities accept that three out of four jobs generated during Fox's presidency (2000–2006) were in the informal sector (INEGI, 2009). At the same time, the number of collective work contracts – trade union negotiations for the improvement of labour conditions and wages – decreased from 5,171 in the year 2000 to 2,364 by mid-2004 (Centro de Derechos Humanos Fray Francisco de Vitoria, 2005).

7 In 2007 there were a total of 343,021 land conflicts and almost the same number of local water conflicts (Procuraduría Agraria, 2008). Of these conflicts 72.1% were related to issues of possession, especially where fraudulent Communal Assemblies (*Asambleas Ejidales*) left women without entitlement rights; to the succession of ejidal or communal rights or to the possession of urban plots. Further, 10.6% of these conflicts were related to problems with the boundaries between ejidos and private propriety, communal land, restitution of the land, forests and water, and 11.48% were conflicts related to issues of ejido membership where new members who have never worked on the land can be accepted by the Assembly as land owners, while small peasants can be expelled without their consent. The remaining conflicts are linked to the extraction of natural resources (mines).

velop productive activities, and to live peacefully with an enhanced quality of life.

23.3.2 Hydrodiplomacy Model

Facing this complex challenge that is further aggravated by an increasing number of water conflicts, an alternative integrated model is proposed here to deal with water at all levels, from the basin and aquifer to the household. Through organization and training, the three key social actors could solve their differences peacefully, and become organized and trained to transform water culture. Hydrodiplomacy means negotiating water conflicts peacefully (figure 23.10). This approach should address the causes of environmental stress, especially those factors that are linked to the lack of water supply due to climate change, poor basin management, river diversion, contamination of surface and groundwater, deforestation, erosion, forest fires, loss of biodiversity, air pollution, desertification, land degradation, drought, etc., as well as to different social factors, such as the rising water demand, population growth, urbanization, industrialization, irrigation, agriculture and livestock, services and wastewater (World Bank/IPRN, 2003). The terms for negotiation can be set afterwards.

While the case of the Río Bravo water basin is an international issue, in Mexico City the water problem has involved local government and an organization of the indigenous Mazahuas, where eventually CONAGUA, the governments of Mexico City and of the state of Mexico intervened (Oswald, 2005). The conflict of the so-called '13 communities of Morelos' for the Chihuahuita spring was between peasants and urban construction firms, where the government of the state of Morelos intervened as an intermediary. The Amatzinac ravine (Morelos) case concerns municipalities in the upper and lower part of the micro-basin and agricultural users who steal the water with small pipes. Another example refers to the well Mancerca II that was drilled in the community of Atlatlahuacan (Morelos), which was to benefit the municipality of Totolapan in the northern part of the same state.

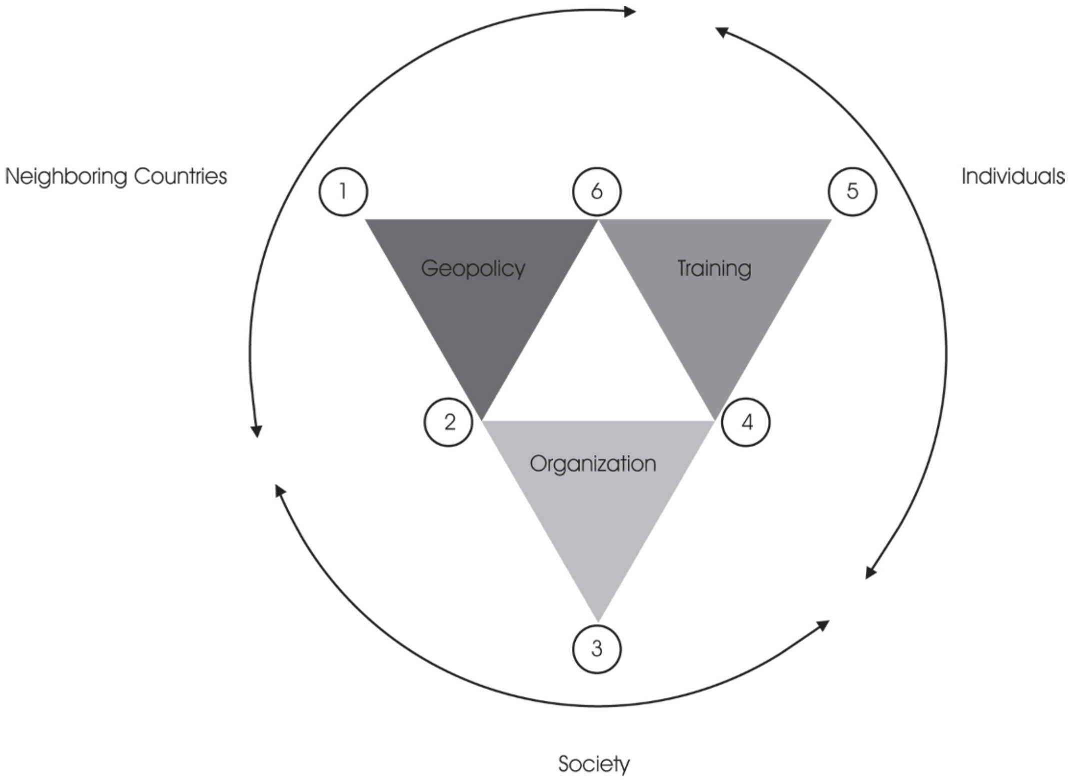
From these examples it is fundamental to avoid the fallacy of decision-making levels during the negotiation process, given that often local and particular lobbies are combined with state or international interests, thus reducing the opportunities to reach an agreement and to solve the problems peacefully. The first step has always been to identify and delimit the problem, to define the levels of controversy and to prevent the conflict from widening. Key actors can be identified through a conflict map: social groups, government entities, businesses or individuals, internal and external allies, enemies, vested interests, beneficiaries, losers, as well as possible solutions that will benefit all parties involved in the conflict.

The second step is to organize the people involved in the conflict and to create common interest groups to define specific demands for the amount and quality of water needed, as well as structuring the different interest groups. This generates expectations between stakeholders, opens up technical solutions, and reduces tensions between groups over time. At the same time, it offers the possibility of articulating the agenda systematically (detailed in figure 23.11). Understanding the limitations in terms of demand, supply, and quality of water, the first mechanisms of negotiation and administration can be established, taking into account the fact that differential prices and subsidies can foster rational use of water and protect the most vulnerable groups. Besides this, through training and organizing demand by social and productive sector, a culture of RRRR can be generated: reducing, reusing, recycling, and retraining in water management, meaning that all stakeholders save water and share it.

When affected groups become organized and trained, an interrelation between both processes is established; this opens the possibility of a 'win-win' situation that will benefit all stakeholders, and of making an agreement viable in the long term. Otherwise, when a group of stakeholders is discriminated against or feels disadvantaged, conflict is likely to re-emerge. Therefore, it is essential to seek for consensual solutions, taking water availability, the level of education, financial, social, and technical factors (point 5 in figure 23.10) into account. Once the problem is defined, feasible technical solutions are sought according to the needs of parties in conflict (point 4). People must be trained to understand the dilemma of lack of water or of a highly polluted resource, and the process of negotiation may begin. The starting point should always focus on the less emotionally charged or easiest-to-solve issues.

In the case of the international basin of the Río Bravo, the conflict has been placed in a geopolitical context, addressing problems between two countries and between the states and communities within each country. In all cases, consensual agreements of mutual benefit must be sought. This requires the organization of all social sectors (point 3). It is easier to work with each sector separately when it is well organized: the primary and industrial sector, the maquila, the service and tertiary sector, as well as water demand by irriga-

Figure 23.10: Hydrodiplomacy. **Source**: Author's elaboration based on Oswald Spring/Davis Mazlum in Davis Mazlum (2004: 19).

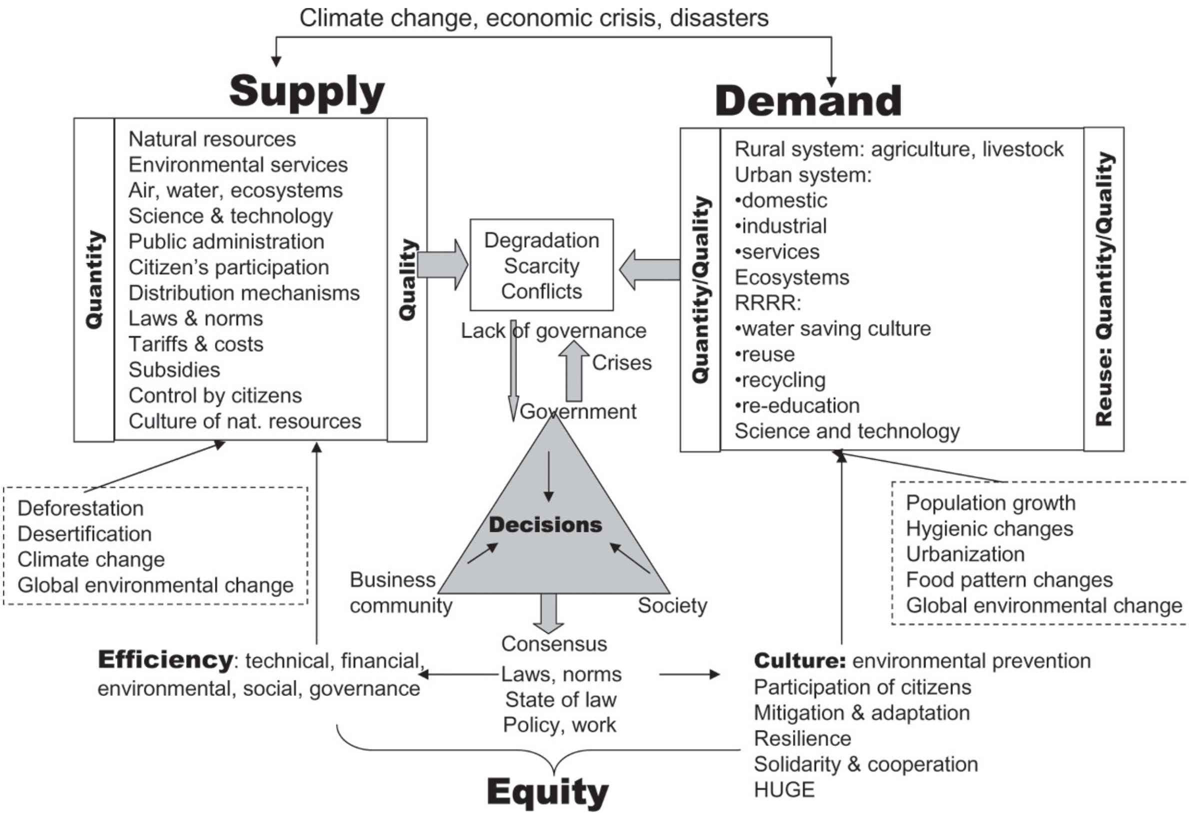


tion districts. Not all productive processes necessitate the same water quality and potable water can be reserved solely for human consumption, whereas agriculture and certain ecosystems can use treated domestic and industrial residual water. Cooling processes can use water of poor quality whereas groundwater can be saved for human use. Extracting less groundwater gives a higher potential for recovering aquifers; this limits land subsidence and structural damage to houses and business premises, as well as damage to the public infrastructure. Also, water use efficiency in agriculture, industry and services can be fostered through water-saving systems, micro-irrigation tunnels, micro-sprinkler systems, etc. Agreements and newly-developed technologies require better training (point 4) to promote changes in water culture and to make the population conscious of water scarcity.

At the same time, in any conflict negotiation it is important to balance forces between different stakeholders (point 2). In the case of the Río Bravo basin and the indigenous Mazahuas there was a clear power imbalance between Mexico City and the Mazahuas as well as the USA and the government of Mexico, respectively. However, in both cases biodiversity and environmental services permitted a mutually beneficial negotiation. For example, a bi-national agreement between Mexico and the USA based on cooperation and political stability allows the USA to benefit from the maquila, generating employment on the Mexican side of the border and reducing illegal immigration and increasing general well-being. Cooperation between both governments and especially the improvement of quality of life for the population helps to combat organized crime and to stabilize the border region.

In the case of the Mazahuas, Mexico City clearly needs the water from the Cutzamala as it has almost depleted all its aquifers. Reforestation, storage infrastructure, potabilization at the Berros treatment plant, and sanitation *in situ* would improve water quality and increase water volume from the source, without depriving the local population of this vital liquid. Supporting agriculture and the environmental sectors in this indigenous zone in the state of Mexico would generate employment opportunities that are currently lacking as well as creating sources of income, and at the same time reward historical indigenous efforts to conserve and care for water. This situation demands a more rational use of water as well as prices that genuinely reflect the costs of operation and conservation.

Figure 23.11: Sustainable Water Management**.** Efficiency and Equity with Natural Resources. **Source:** Developed by the author.



Realistic prices would provide incentives to save water and offer Mexico City's water supply system the necessary resources to repair leaks and improve the quality of their services[8]. In the Mazahua region, through an integrated development plan, poverty could be alleviated and migration to the USA could be stopped, reinforcing environmental services, water quality, and generating overall well-being for the city and the rural areas.

The process of integrated management of conflicts is complex and requires creativity, tenacity, patience, commitment, and especially abiding by agreements. In order to reinforce competencies between the parties in dispute and negotiators, intensive training courses must be given to outline all stages of negotiation (point 4). In this process, no group should be discriminated or oppressed. Instead, the mechanisms to monitor the implementation of the agreement should be institutionalized. Given that this process may take years, conciliation itself becomes ongoing training, allowing parties to reach new agreements on new issues that emerge as time goes by (point 6; figure 23.10).

23.4 Concluding Remarks

Reaching greater, profound, and lasting agreements as a result of this negotiation process requires the use of all existing capital, for example social capital including solidarity and cooperation; economic capital in terms of money, labour, technology and administration; political capital such as transparency, governance, civil participation and monitoring agreements; cultural capital including traditional water conservation habits, rainwater harvesting, efficient water use, reuse and recycling of wastewater for irrigation and gardening; and environmental capital including the

8 According to estimates, about 35 and 55 per cent of potable water leaks away, and 25 per cent is wasted in households. Sending wastewater to the Valley of Mezquital deprives the capital city of the use of recycled water for industry, irrigation of gardens and parks, toilet flushing, and other services that do not require potable water. As well as this, on the way, wastewater gets mixed with and pollutes clean rain and river waters.

restoration of ecosystems and people's mental and physical health.

Through this integrated process of water conflict management, unforeseen goals can be achieved. More importantly, a new development plan for the country could be negotiated, deepening and widening security into a 'HUGE' paradigm: one of human, gender and environmental security (Oswald, 2009; Oswald/Brauch, 2009). This would also overcome traditional pitfalls in legislation, involving citizens directly in the drafting and application of norms and decrees in favour of efficient and integrated water management. On the technical and financial front, greater efficiency and transparency may be attained. A participatory democratic and equitable future for Mexico starts with grass-roots mobilization, and it relates to water issues, to forging a sustainable water culture, and to developing resilience and training to face the challenges of global climate change (figure 23.11).

This participatory effort can improve the interaction of water with vegetation and land resources, reducing water stress. Special emphasis should be given to reforestation and the care of rivers and streams. At the same time, a democratic territorial ordering should be promoted, with the participation of all citizens, including women, children and the elderly, and with the firm resolution of sustainable management of water, the ecosystem, and its natural resources including forests, food production, and industrial inputs. With an alternative agrarian policy, additional domestic employment could be generated, quality of life in rural areas could improve, and the pressure for international and urban migration could be reduced. Environmental planning in Mexico enhances the potential for fighting water scarcity and pollution, as well as preparing the people more effectively for the new and escalating risks related to climate change.

The reordering of the physical territories has an impact on the socio-political and cultural spaces where labour and goods can be regulated. Governments and civil and business institutions are key actors in a complex web of beliefs, behaviours and holistic perceptions of reality that combine local histories capable of preventing risks, mitigating dangers and consolidating resilience. Environmental culture is part of identity (Serrano, 2004) and of ideological processes (Giménez, 2005), where productive processes and human needs link to existing systems of social representation (Flores, 2001). The appropriation of knowledge for environmental management expresses a structured and coherent vision of the environment, or of "cosmovision", the holistic perception of reality where human life interrelates with the cosmos and situates human activities (Broda, 1997; Broda/Good, 2004). It is precisely these deeply rooted forms of behaviour that underlie all negotiation processes. Overall, hydrodiplomacy aims at peacefully consolidating conflicts based on the rule of law with clear norms and costs that must be applied without discrimination, and enabling an integrated environmental management that renews existing water cultures for the benefit of all.

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24 Distribution of Surface Water of the Rio Bravo between Mexico and the United States

Vicente Germán Soto and José Luis Escobedo Sagaz

24.1 Introduction[1]

This chapter analyses the effect of the official institutions set up by Mexico and the United States for the allocation of the surface water of the Rio Bravo (Rio Grande) based on the convention of 1906 and the water treaty of 1944. For the assessment of institutional impacts, the empirical evidence is based on the annual average water flows provided by the *International Boundary and Water Commission* (IBWC), which rely in turn on twelve measurement points located along the Rio Bravo for the period from 1933 to 2005. Results from a regression analysis indicate a climate of respect for the agreements and treaties reached by both nations on this issue. Estimates and regressions suggest that changes and variations in water flows are due to modifications to these treaties, to the construction of hydraulic infrastructure, and to dry seasons. However, controlling for random events made it possible to demonstrate that water flows were constant. This result is interpreted as being statistically significant evidence that bilateral treaties and norms concerning the distribution of surface water were respected during the period studied.

As society developed, the demand for natural resources increased, generating greater scarcity and making it indispensable to put adequate resource management in place so as to guarantee the optimal use of these resources. Nowadays, there is greater awareness of this. However, efficient management becomes more difficult when resources are shared by two or more countries. For many years, a pressing issue for bilateral relations between Mexico and the USA has been the distribution of the Rio Bravo's surface waters. In the light of the importance of this topic for societal well-being and the poor attention it has received in the economic literature, this chapter analyses the bilateral distribution of water in order to assess the effects of the agreements signed by both countries.

The difficulties in cross-border natural resource management are particularly severe in the case of water. Water is a scarce natural resource that is vital for human survival at many levels; since it has no substitute, possession of water is a strategic concern for economic development and for human settlements. Its distribution ignores political frontiers, fluctuates in space and time, and has competing demands for its use, and this has led to many conflicts. Throughout history, some disputes have escalated to armed conflicts, and currently this situation is expected to be exacerbated in certain regions (Wolf 1998: 252).

Countries try to make agreements that will avoid or minimize conflicts, and they seek solutions at minimum cost, such as the agreements signed by Mexico and the USA on the management of the most important trans-border basin. Institutions emerging from these agreements have been considered by cross-border water experts as role models in water conflict resolution. Even though these institutions have a long history in the relations between Mexico and the USA, they are increasingly being questioned by the academic community, because of their current performance and because of the absence of elements of sustainable development.

In recent years, water as a research topic has necessitated studies from many disciplines covering a wide range of aspects. Specifically, the distribution of trans-border water in the Rio Bravo has become a topic of heated debate. Examples are the studies by DeBuys (2001) focusing on flora and fauna and the impact of human activities on areas in the higher basin. Other studies conducted by Barajas (1999), Hume (1999), Martínez (1999), Mumme (1999), Ingram (1999), and Utton (1999) have stressed the problems of hydraulic resource management after the droughts of the 1990s. Also following these droughts, Chávez

1 Keywords: Water, Rio Grande, institutions, time series, unit roots

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_24,

(1999), Hurlburt (2001), Ingram and White (1993), Mumme and Bustamante (1993), Mumme (2003), Schoik and Brown (2004), and Szekely and Cabrera (1993) have discussed the performance of the institutions controlling water management in the Rio Bravo.

Authors such as Arias (2000), Chávez (2000), Durant and Holmes (1985), Gantz (1996), Hume (2000), Johnstone (1995), Jones (2002), and West (2003) offer an overview of hydraulic and environmental policies in the basin. Yoskowitz (1999) highlights the price system as a hydraulic resource management mechanism for guaranteeing the future development of the region.

Brown and Mumme (2000) discuss the resort to basin councils as an indispensable mechanism for guaranteeing sustainable development in the systems located in Tijuana and the Rio Bravo. The authors question the limits set by the IBWC for the implementation of an optimal resource management.

Cortez, Whiteford, and Chávez (2005) review a series of studies analysing the water situation in the border and its relation to security in both countries, including legal and institutional aspects linked to cross-border waters, and social equity in water management.

The Mexican-US cross-border waters are especially important because of the natural conditions in most parts of this region: low levels of rainfall, scarce water availability, and recurrent drought. Besides this, current development trends, characterized by high population and economic growth rates, have led to an imbalance in water demand and supply, with severe implications for potential future conflicts for which preparation is needed.

Cross-border water management is affected by various existing asymmetries between Mexico and the USA, including political, economic, and water availability asymmetries. In all these cases the USA is favoured, although political and economic asymmetries are more prominent. This chapter analyses the problems generated by the asymmetry of water availability, focusing on the institutions in charge of surface water management in the Rio Bravo basin and the water flows as reported by the IBWC.

This chapter is divided into six sections. Following this introduction, the second section outlines the research objective and hypotheses (24.2), while the third focuses on data description, information sources, and the water flow measuring points (24.3). The fourth section presents the methodology used in the study (24.4), and this is followed by an analysis of results (24.5), and some concluding remarks (24.6).

24.2 Objective and Hypothesis

24.2.1 Research Objective

This chapter analyses the historical distribution of surface water in the Mexico-US cross-border Rio Bravo Basin to determine water availability based on the convention on "Equitable Distribution of the Waters of the Rio Bravo" (1906) and the treaty on "Utilization of Waters of the Colorado and Tijuana rivers and of the Rio Bravo" (1944).

The distribution of surface water is an indicator of institutional performance and of the ways in which societies adapt their patterns of resource appropriation to match the institutional framework. Following the droughts in the 1990s, some authors, such as Mumme (1999) and Ingram (1999), have questioned institutional efficiency, and have suggested possible solutions, such as an integral basin management which emphasizes the way in which water users have been part of water management; their analysis uses the joint USA-Canada Commission as a comparison.

24.2.2 Hypothesis

This chapter only addresses the impact of formal institutions on water allocation in Mexico and the USA. It is therefore not possible to evaluate other impacts, such as those derived from informal institutions, which limit these findings. Nevertheless, it is assumed that present, informal impacts are not as relevant as those derived from formal institutions. In this sense, the goal is to prove the hypothesis that water flows have a normal distribution and have no changing trends over time (they remain constant), as treaties and agreements fix a water volume as constant. However, as institutions have been modified over time, the aim is to find one or two structural changes – occurring in dates close to the treaty modification periods – that have affected water flow levels, although once implemented they maintain a constant evolutionary trend. To prove this general hypothesis, three particular hypotheses will be tested:

Hypothesis 1: Average water flows have a normal distribution. They only show flow level variations between structural changes, and remain constant over time following such changes. Structural changes can be the result of external factors such as institutional changes (new bilateral laws regarding water appropriation), drought periods, or dam and infrastructure construction.

Hypothesis 2: Average water flows have a normal distribution, although they are not constant since water flow volumes vary across time. They mark an ascending or descending trend linked to structural changes such as institutional change (new bilateral agreements on water allocation) and drought periods, as well as dam and infrastructure construction.

Hypothesis 3: Average water flows are asymmetrically distributed and they show changes in level and slope that are accentuated with time. After controlling for structural changes, water flow variations across time persist.

Hypothesis 1 is important in enabling the provision of evidence that treaties and binational norms regarding surface water are being respected. After controlling for structural changes throughout the period under study, and as a consequence of factors external to new institutional norms leading to increases or decreases in water levels, it is empirically verified that new water levels do not present substantial alterations. Out of the three particular hypotheses, we expect hypothesis 1 to occur in the measuring points that make up our sample.

Hypothesis 2 is closely linked to hypothesis 1; however, as it evolves across a lineal timeframe the existence of some type of governance is assumed that continuously alters water flow throughout the period (increasing or decreasing it). If proven, this hypothesis would provide limited empirical evidence that institutional norms and treaties are being respected.

Hypothesis 3 suggests that there is no valid empirical evidence to sustain the belief that institutional norms and treaties are being respected. Thus, in theory, it is hoped that none of the water flow measuring points will validate it.

24.3 Description of Water Flow Measuring Points

The source of information has been the US part of the IBWC with its over 80 water flow measuring points along the Rio Bravo basin, generating daily information on water flow measured in cubic metres per second (m^3/sec). Available data[2] offer great historical variety: some series start at the end of the 19th century, but most begin after the signing of the 1944 Treaty. Most data series present a delay of six months up to one year, but some measuring points no longer report recent information. Initially, only measuring points regulated by existing binational agreements were included. This explains why sub-basins where Mexico does not receive any water were ignored, e.g. the measuring points in the Pecos river.

In the first selection, 42 series were obtained; however, at the end of the analysis a second selection was made. The criterion was that the observation order would be the same and that it would comprise the years prior to the signing of the 1944 Treaty, when a structural change in water volumes delivered from the USA to Mexico took place (Germán Soto/Escobedo 2008).

In the second selection, the data series were reduced from 42 to 12, and as their measuring points are distributed across the Rio Bravo, it is possible to observe the influence both countries have on water flows (figure 24.1). The 12 water flow measuring points are the following: (1) under the dam 'Elephant'; (2) at El Paso, Texas; (3) in Fort Quitman, Texas; (4) above the Conchos river near Presidio, Texas and Ojinaga, Chihuahua; (5) at the 'Alamito' creek near Presidio, Texas; (6) below the Conchos river near the Presidio river; (7) at the Terlingua Creek near Terlingua, Texas; (8) in the San Diego river near Jiménez, Coahuila; (9) close to Piedras Negras, Coahuila; (10) at the Escondido river near Villa Fuente, Coahuila; (11) next to Laredo, Texas; and (12) close to Matamoros, Tamaulipas.

The twelve series used in this study start in 1933 and end in 2005. Initially, all are available as daily averages, although this level of measurement presents some difficulties for the treatment of the data, for example, being too extensive and sensitive to small and diverse seasonal variations, impeding the documentation of more relevant factors for this study, such as institutional ones. For this reason, yearly averages were used.

The water flow measuring points are representative of some interesting situations. The first point, located below the 'Elephant' dam, is part of the waters that are allocated to Mexico. In this way, with this series the impact of users in the higher basin can be identified in the allocation of water resources through the hydraulic infrastructure built for this purpose and stipulated in the 1906 Convention.

The measuring points at El Paso and Fort Quitman mark the water deliveries from the USA to Mexico, as well as the allocation of water by Mexico. According to the 1906 Convention, water delivered by the USA should be used for developing an irrigation district in the region. In these measuring points one

2 See at: <http://www.ibwc.state.gov/Water_Data/histflo1.htm> (29 January 2009).

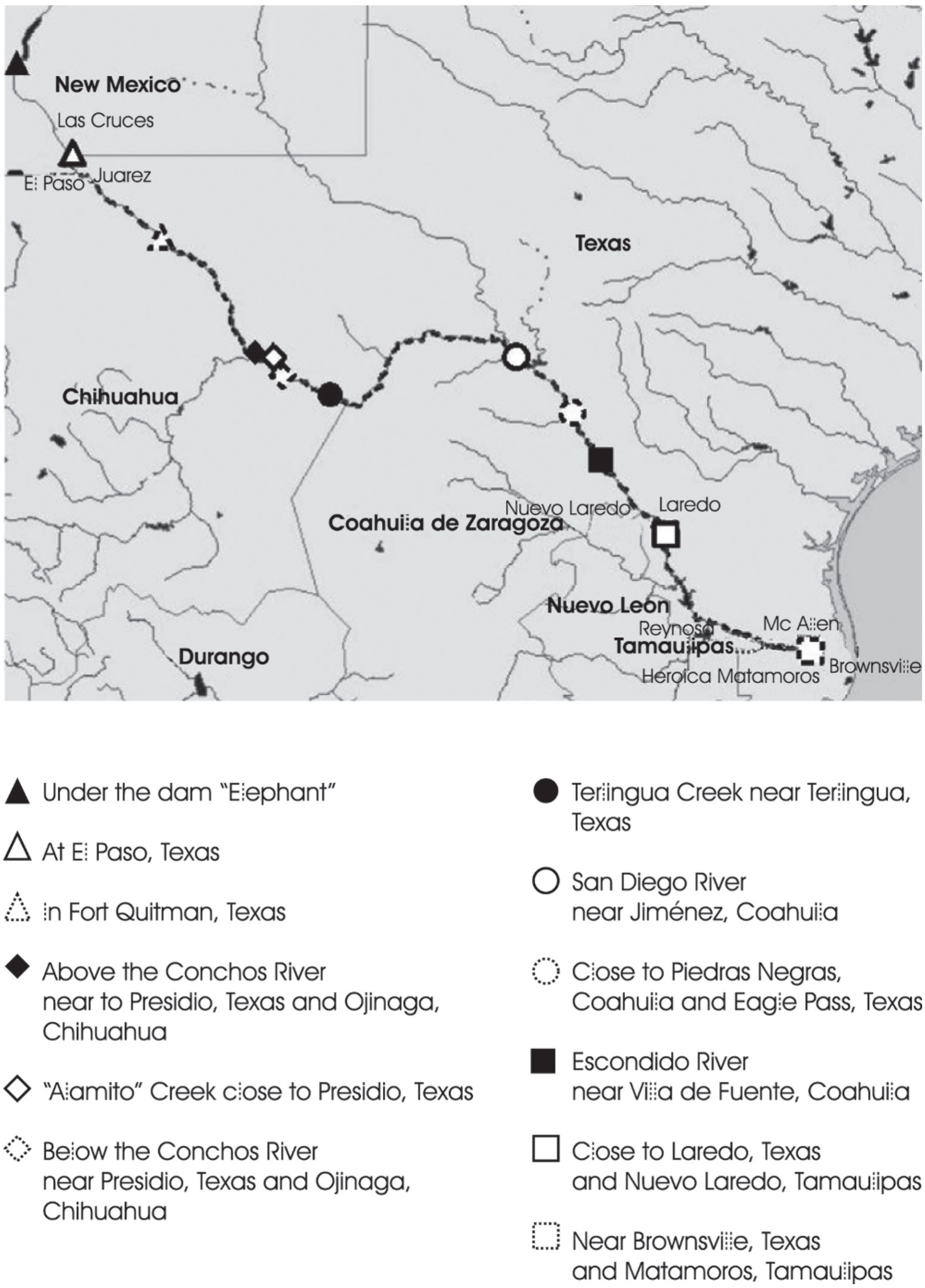

Figure 24.1: Location of the twelve water flow measuring points. **Source:** Authors' elaboration using Geographical Information System (GIS) data; at: <http://gisdata.usgs.gov/website/ibwc/viewer.htm>.

can expect to see more clearly the influence of US and binational institutions, as the sub-basin has been created and managed by existing institutional rather than natural conditions (Escobedo, 2008).

The stretch situated above and below the Conchos river helps to identify the behaviour of Mexican users in the irrigation districts of Chihuahua and their adaptation to the 1944 Treaty which obliged them to deliver a part of the Conchos river waters to the USA. These deliveries are the main source of conflicts between Mexico and the USA – especially in the dry season and in Texas – as they represent the most important surface water source in the basin, affecting North American users located above the Pecos river and the dam 'La Amistad'. At this measuring point it is possible to expect a structural change in water flows after the 1944 Treaty.

The next point of interest is the measuring station located close to Piedras Negras, where the dam 'La Amistad' was built, possibly altering water flow levels. Some important dates to bear in mind at this measuring point are: the start of dynamiting and engineering works (July 1963); the start of construction works (January 1965); the moment when waters for the dam began being collected (July 1968); the end of the dam's construction (August 1969); and the date of the official inauguration of 'La Amistad' (September 1969). Thus, a change around the years 1968, 1969, or just afterwards may be expected.

Finally, attention is focused on the measuring station next to Brownsville and Matamoros, as it corresponds to the construction of the 'Falcon' dam. For this water flow measuring point the crucial dates to bear in mind are: the start of construction works (December 1950); the beginning of water collection (December 1952); the official inauguration date (October 1953); and the end of its construction (April 1954). Thus, structural changes are expected to be seen between 1953 and 1954.

Observing the series one can consider at least four groups with an initial maximum flow and its subsequent decline. The first group runs from the 'Elephant' dam to the 'Alamito' creek, the second group extends from the point above the Conchos river to the San Diego river, the third starts in Piedras Negras and ends close to Laredo, and the fourth corresponds to the measuring point next to Matamoros. It can therefore be seen that the data reflect these aforementioned situations of special interest.

However, it is also important to bear in mind that in those changes following the construction of the dams which directly correspond to infrastructure determinants, the role of institutions manifests itself in two ways: on the one hand, the 1944 Treaty stipulates the construction of these two dams (it provides for the construction of a third dam, although this has not been considered necessary yet), and on the other hand, the IBWC controls the administration of the dams.

24.4 Methodology

In order to contrast the set of hypotheses, regression analysis was used to test changes in trends and constant rates in a data set evolving over time. This methodology is known as time series analysis and it presents some advantages in the analysis of data such as the Rio Bravo water flows. For example, it analyses a historical data set and its evolution with regard to a constant or a linear trend, or it enables us to know whether the data set underwent a structural change over time in the period under analysis (that is to say it is not *a priori* imposed). In the case under study, finding structural changes is relevant. Statistically significant changes would provide information as to whether changes are due to institutional transformations, or they could suggest that bilateral institutional agreements are not being respected. In either case, the magnitude and direction of structural changes can provide an idea of increased or decreased water flows at each measuring point.

The time series approach is based on the analysis of the mean, variance, and covariance of a data set in order to see changes across time. Its standard formulation is based on a regression equation such as the following:

$$y_t = \beta_0 + \beta_1 t + \beta_2 y_{t-1} + u_t \quad (1)$$

where y_t is the variable of interest (average annual water flow at each measuring point on the Rio Bravo); t is a linear trend; y_{t-1} is the value of the dependent variable lagged one period, and u_t is the random error with mean zero and constant variance.

If $\beta_0 = \beta_1 = 0$ (i.e., neither the constant nor the linear trends are significant) and also $\beta_2 = 1$ then equation (1) becomes:

$$y_t = y_{t-1} + u_t \quad (2)$$

and this means that the evolution of the variable is conditioned to its past value and to the random error terms from period 1 till period t. The model represented by equation (2) is known as the random walk model with no variation. This model has a non-stationary nature, implying that the historical data set cannot be used in order to make forecasts. Also, it may be found that $\beta_0 \neq 0$, $\beta_1 = 0$, $\beta_2 = 1$, so:

$$y_t = \beta_0 + y_{t-1} + u_t \quad (3)$$

In this case, a random walk model with variations may be found, and consequently its nature is non-stationary, as its mean depends on the constant β_0. It may also be possible to find that $\beta_0 \neq 0$, $\beta_1 \neq 0$, $\beta_2 = 0$, which would make equation (1) turn into:

$$y_t = \beta_0 + \beta_1 t + u_t \quad (4)$$

Equation (4) also represents a non-stationary process, given that the mean is altered according to the linear trend. However, there are other possibilities such as $\beta_o \neq 0$, $\beta_1 \neq 0$, $\beta_2 = 1$, that is to say, what is known as a random walk model with variations and a linear trend:

$$y_t = \beta_0 + \beta_1 t + y_{t-1} + u_t \quad (5)$$

The process described by equation (5) is non-stationary. Finally, we may also obtain a linear trend model with a stationary component. In this case $\beta_o \neq 0$, $\beta_1 \neq 0$, $\beta_2 < 1$:

$$y_t = \beta_0 + \beta_1 t + \beta_2 y_{t-1} + u_t \quad (6)$$

Equation (1), which is equal to equation (6), is now turned into a stationary process around a linear trend.

In any of the aforementioned situations where β_2 takes values 0 or 1 – equations (2) to (5) - the process of the data set turns out to be non-stationary, and thus it cannot be used in order to make forecasts. Especially, when β_2 is 1, we say that the series contains a unit root, meaning that the mean and variance are unstable. For this reason, it is important to research whether the series are described by a unit root process or not.

If a series is described by a unit root process, it is necessary to treat it as a first difference series in order to make it stationary. In the literature, various contrasts have been proposed in order to research stationarity in time series. In this chapter two sets of contrasts are taken: those that test a unit root without considering structural changes and those that consider the possibility that a series will be affected by structural changes.

24.4.1 24.4.1. Unit Root Tests without Structural Changes

If water flows have not varied across time and institutional changes have not greatly affected them, then it is sufficient to make unit root tests that consider no structural changes as such.

Let $\{y_t\}$ be a stochastic process generated according to equation (1), for which case Elliot, Rothenberg, and Stock (1996) developed an appropriate asymptotic structure in order to compare statistics to prove a unit root. Our particular interest is the null hypothesis $\beta_2 = 0$ (which means that y_t are integrated of order 1, and consequently they are non-stationary) versus the alternative $|\beta_2| < 1$ (which means that y_t are integrated of order 0, and thus are stationary). In order to test these hypotheses we use the Augmented Dickey-Fuller (ADF) test and the statistical modification proposal by Ng and Perron (2001), which have been proved to present better results in terms of potency and size in small samples. These statistics are based in the generalized least squares technique (GLS), as developed in Elliot, Rothenberg, and Stock (1996). They are calculated as follows:

ADF-GLS:

$$y_t = \beta_0 + \beta_1 t + \beta_2 y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \quad (7)$$

$$MZ_\alpha^{GLS} = \left(T^{-1}\tilde{y}_T^2 - s_{AR}^2\right)\left(2T^{-2}\sum_{t=1}^{T}\tilde{y}_{t-1}^2\right)^{-1} \quad (8)$$

$$MSB^{GLS} = \left(\left(T^{-2}\sum_{t=1}^{T}\tilde{y}_{t-1}^2\right) s_{AR}^2\right)^{1/2} \quad (9)$$

$$MZ_t^{GLS} = MZ_\alpha^{GLS} \times MSB^{GLS} \quad (10)$$

where T refers to the temporal dimension of the series, s^2 is a variance estimator, and the remaining terms are the same as defined previously. Generally, empirical works contrast the null hypothesis of the unit root with the other alternative that the series be stationary, i.e., without structural change.

24.4.2 Unit Root Tests with Structural Changes

When institutional changes are important in altering the trend of water flow series, the previously described unit root statistical methods are incapable of detecting the series' stationarity, as they do not account for the possibility of the occurrence of substantial changes in the first and second moments (i.e., in the mean and variance).

The models presented in this chapter test the unit root hypothesis, enabling the possibility of structural changes of the water distribution series in 1 and 2 (the mean and slope), presented according to dates that are endogenously determined by the model. In general, these models value the conduct of series based on a modified structure of the Dickey and Fuller unit root tests (1979).

The works that research time series characterized by structural changes test the null hypothesis that a given series $\{y_t\}_1^T$ present a unit root where an exogenous structural change in date 1 < TB < T occurs, against the alternative hypothesis that the series is stationary with an exogenous change occurring in date TB.

In the analysis of macroeconomic series Perron (1989), Perron and Vogelsang (1992), and Zivot and Andrews (1992) used an Augmented Dickey-Fuller testing strategy for the unit root, in the following equations:

$$\text{Model } A: \; y_t = \mu + \beta t + \theta_1 DU_t + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_t \quad (11)$$

$$\text{Model } An: \; y_t = \mu + \theta_1 DU_t + D(TB)_t + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_t \quad (12)$$

$$\text{Model } C: \; y_t = \mu + \theta DU_t + \beta t + \gamma DT_t^* + dD(TB)_t + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_t \quad (13)$$

where *D(TB) = 1* if *t = TB+1*, or else 0; $DU_t = 1$ if $t > TB$, or else 0; *D(TB) = t – TB* if *t > TB*, or else 0. The additional *k* elements in the regression are added in order to eliminate any possibility or serial self-correlation. Model *A* enables an exogenous change in the series due to a linear trend; model *An* enables an exogenous change in the series without a linear trend; and model *C* considers both changes. Based on these equations, Perron (1989) and Perron and Vogelsang (1992) derived asymptotic distributions for these statistics and tabulated their critical values for a selected group of λ values in the unitary interval.

Subsequently, Lumsdaine and Papell (1997) extended the methodology of endogenous change in order to enable the alternative of two changes. The authors observed that if unit root tests which included a structural change did not find much evidence to reject the null hypothesis; this could be due to the fact that series were affected by more than one structural change. The models they considered enabled researchers to account for two changes in one of the following alternatives: only in the series, only in the slope, and both in the level in the series and in the slope. Incorporating these two structural changes modifies equations (11), (12) and (13) in the following way:

$$\text{Model } AA: \; y_t = \mu + \beta t + \theta_1 DU1_t + \theta_2 DU2_t + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_t \quad (14)$$

$$\text{Model } AAn: \; y_t = \mu + \theta_1 DU1_t + \theta_2 DU + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_t \quad (15)$$

$$\text{Model } CC: y_t = \mu + \beta t + \theta_1 DU1_t + \gamma_1 DT^* 1_t + \theta_2 DU2_t + \gamma_2 DT^* 2_t + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + \varepsilon_i \quad (16)$$

where $DU1_t$ and $DU2_t$ are indicators of fictitious variables for change in the mean for dates *TB1* and *TB2* respectively, and DT^*1_t and DT^*2_t are the variables corresponding to trend changes. The values of fictitious variables are as follows: $DU1_t = 1$ for $t > TB1$, $DU2_t = 1$ for $t > TB2$, $DT^*1_t = (t - TB1)$ for $t > TB1$, $DT^*2_t = (t - TB2)$ for $t > TB2$, 0 in all other cases. Specifying *AAn* stems from the work by Carrion-i-Silvestre et al. (2004), and it constitutes an alternative of two structural changes in the series' mean that have no trend. *AA* and *CC* were taken from the work by Lumsdaine and Papell (1997).

The parameter of interest in equations (11) to (16) is α (also known as the ADF coefficient). If it proves to be statistically significant, it would provide empirical evidence that the series is stationary with one or two structural changes occurring in some date of the period under analysis and in one of the functional forms described by the equations. Also, in order to select the most adequate functional form for each data series we used the *Bayesian information criterion* (BIC), as the possibility that a data series estimates a significant α value in more than one model exists.

The group of equations (11) to (16) can be related to the hypotheses in our work in the following way. If for a determined series of water flow modes *An* and *AAn* are selected, then hypothesis 1 holds. If models *A* and *AA* are selected, then hypothesis 2 holds. And if models *C* and *CC* are most adequate, then empirical evidence supports hypothesis 3. As was argued above, it is hoped to find evidence that behaviour confirms compliance with norms and rules which regulate access to water, which would imply that the models that ought to be validated are models *An* and *AAn*, confirming hypothesis 1. Instead, models which suggest the opposite would be models *C* and *CC*, which it is hoped will not stand.

24.4.3 Estimation Process

Equations (11) to (16) were estimated at each water flow measuring point for the period 1933–2005. The program builds estimates of the variables of coefficients and endogenously selects – through data analysis – the year in which structural changes occurred. The process used in order to detect two structural changes excludes the possibility that two structural changes take place at consecutive dates. This means, for example, that a positive change followed by a negative change (or the inverse) are not taken as two separate processes.

There are some considerations to be taken into account on how the program works. First, the program determines the optimal lag for each possible breaking point (structural change) and then it looks for the point of rupture. The critical value to determine a possible breaking or rupture point is fixed at a statistical value of t equal to 1.645. The maximum lag is $k = 5$, and 10 per cent of the extreme points of the sample cannot be considered as possible optimal rupture points *(TB).* The appropriate values for *TB* and k are unknown, which implies that the program determines these values endogenously. Given that there is considerable evidence that the data-dependent methods for selecting the lagged value of k are superior to the selection of an *a priori* fixed value for k, this chapter follows Zivot and Andrews (1992) and uses the procedure suggested by Ng and Perron (1995). This procedure starts with an upper limit k_{max} for k. If the last lag is significant, $k = k_{max}$ is chosen; otherwise, the value for k diminishes by 1 until the last lag becomes significant. If none of the lagged values are significant, then $k = 0$ is considered.[3]

24.5 Results

Table 24.1 shows the unit root results of the twelve water flow measuring points without structural change. The values calculated with the four contrasts described in the previous sections are presented for the two functional forms of water flows: the first considers that they evolved from a constant, and the second considers the importance of the trend of the series.

Generally, with both functional forms the data series at measuring points 1, 2, and 11 proved to be stationary at a significance level of 5 or 10 per cent, as the four contrasts agree in rejecting the unit root null hypothesis. In practical terms, in measuring stations 1, 2, and 11, water flows have been constant and there is no statistical evidence which suggests that agreements and norms surrounding water distribution and appropriation have not been respected. In particular, at measuring points 1 and 2 results provide strong statistical evidence to support hypothesis 1, as they constitute a sub-basin bound by the institutions set by the 1906 Convention and not by natural conditions.

However, in the remaining measuring spots, there is greater disagreement according to the contrasts implemented, as some point towards the stationarity of the series, whereas others highlight the contrary. This can be due to the fact that in these cases, data can be dominated by structural changes that have not been accounted for.

In table 24.2 the result of equations (11) to (16) are presented, and the possibility of structural changes is considered, providing information of the functional form of the series, as well as of the year or years when the structural changes took place.

The estimated *ADF* coefficient turned out to be significant in all series except for two: 2 and 12. In those cases, where it was significant, the result indicates that important changes which modified average water flows took place, implying that it was necessary to account for this possibility in order to make the series stationary. Regarding series 2, it may be explained because unit root tests without structural changes were already stationary, whereas in the case of series 12 wider explanations must be sought, for it was not possible to make it stationary even when accounting for two structural changes[4]. An explanation for this may be the possibility that this series is characterized by more than two structural changes, a situation that goes beyond the limits of analysis of the present work. In any case, the results suggest great variation in water flows due not only to institutional factors, but also to other kinds of events such as droughts, dam construction, or population growth in the area.

The selection of models provides important information regarding this work's hypotheses. In seven out of the twelve measuring points, models *An* and *AAn*

3 Ng and Perron (1995), and subsequently Ng and Perron (2001), used simulations in order to demonstrate that these tests prove an advantage when compared with methods based on information, as they produce more robust tests without losing much potency.

4 However, series 12 turned out to be stationary with models A and C, with the year 1965 selected as the point of structural change in both cases, although BIC selected the AA model as most adequate.

Table 24.1: Unit root results, without structural change. **Source:** Authors' research data.

Num	Water flow measuring points	k	MZ_α	MZ_t	MSB	ADF-GLS
		In the function of a constant				
1	After the Elephant Butte Dam (New Mexico)	4	-11.40 **	-2.31 **	0.20 **	-2.31 **
2	El Paso (Texas)	2	-12.15 **	-2.37 **	0.19 **	-2.43 **
3	Fort Quitman (Texas)	3	-4.44	-1.47	0.33	-1.48
4	Before the Conchos River and near the Presidio River	3	-3.21	-1.26	0.39	-1.30
5	Alamito Creek (Texas)	5	-1.57	-0.67	0.43	-1.66
6	After the Conchos River (near the Presidio River)	2	-5.71 *	-1.61	0.28	-1.47
7	Terlingua Creek (Texas)	3	-11.77 **	-2.20 **	0.19 **	-2.79 **
8	San Diego River, nearby Jiménez (Coahuila)	4	-9.26 **	-2.13 **	0.23 **	-2.47 **
9	Piedras Negras	4	-5.39	-1.50	0.28	-1.57
10	Escondido River (Coahuila)	4	-4.96	-1.39	0.28	-1.94 *
11	Nuevo Laredo	3	-8.96 **	-2.07 **	0.23 **	-2.02 **
12	Matamoros (Tamaulipas)	4	-3.64	-1.34	0.37	-1.23
		In the function of a linear trend				
1	After the Elephant Butte Dam (New Mexico)	2	-16.48 *	-2.85 *	0.17 *	-3.02 **
2	El Paso (Texas)	0	-17.24 *	-2.92 **	0.17 *	-3.41 **
3	Fort Quitman (Texas)	3	-5.19	-1.61	0.31	-1.63
4	Before the Conchos River and near the Presidio River	3	-3.68	-1.35	0.37	-1.44
5	Alamito Creek (Texas)	5	-1.66	-0.69	0.42	-1.68
6	After the Conchos River (near the Presidio River)	2	-9.85	-2.22	0.22	-2.41
7	Terlingua Creek (Texas)	3	-13.09	-2.47	0.19	-2.91 **
8	San Diego River, nearby Jiménez (Coahuila)	4	-13.73	-2.58	0.19	-2.83 *
9	Piedras Negras	2	-13.66	-2.61	0.19	-3.14 **
10	Escondido River (Coahuila)	4	-7.51	-1.74	0.23	-2.31
11	Nuevo Laredo	2	-14.89 *	-2.73 *	0.18 *	-2.82 *
12	Matamoros (Tamaulipas)	4	-11.75	-2.33	0.20	-2.34

*Notes: The lag number for k, for the self-regressive correlation, is optimally selected with the Modified Akaike Information Criterion (MAIC) by Ng and Perron (2001) with a maximum k = 5. When there is a constant, the critical values at 5 and 10 per cent are (respectively): for Mza (-8.1 and -5.7); MZt (-1.98 and -1.62): MSB (0.233 and 0.275); and ADF-GLS (-1.98 and 1.62). According to the linear trend, critical values at 5 and 10 per cent are: Mza (-17.3 and -14.2); MZt (-2.91 and -2.62), MSB (0.168 and 0.185) and ADF-GLS (-2.91 and -2.62). In all tests the unit root null hypothesis is contrasted with the stationary alternative. The stars ** and * indicate significance levels at 5 and 10 per cent respectively.*

were selected, providing evidence to support hypothesis 1. This means that in most measuring stations, water levels have been uniform and constant, which favours the framework of respect for institutional norms and treaties. In another four series, the model selected was *AA*, which provides evidence in favour of hypothesis 2. In this case, results highlight constancy in water levels, despite a light negative temporal trend in three out of the four. Given that changes in the constant were more salient than slope changes, we conclude that water appropriation is within the boundaries set by bilateral institutions. Finally, there was only one case where constant and slope estimations lead us to suppose that the institutional framework has not been favoured. This is the case of series 7, belonging to Terlingua Creek, Texas.

In eleven series, one of the models that estimate two structural changes was selected, whereas only in one series was the consideration of one structural change enough to attain the series' stationarity. These results indicate that during the period analysed, there have been at least two important structural changes modifying the Rio Bravo's water levels. It is possible to identify the causes for some of these changes. For example, series 4 and 6 (corresponding to measuring points located above and below the Conchos river) enable us to identify the structural changes occurring in 1946 and 1947, which reflect the implementation of the 1944 Treaty by Mexican users. The second structural change in those series (1983 and 1996, respectively) intuitively reflects droughts in those years, which has been one of the main causes of conflict between Mexico and the USA. Other series that

Table 24.2: Unit root results, with 1 and 2 structural changes. **Source:** Authors' research data.

Place	Model	TB1	TB2	μ	β	θ_1	γ_1	θ_2	γ_2	ADF	k
1	AAn	1953	1956	2.0787		-0.8053		0.7087		-0.6166	0
				(5.7112)		(-3.6967)		(3.5097)		**(-5.8805)** ***	
2	An	1963		0.8469		0.0389	-1.5353			-0.3275	0
				(3.7338)		(0.4093)	(-3.8540)			(-4.0654)	
3	AAn	1950	1971	1.0968		-1.4236		1.2160		-0.5732	0
				(3.8550)		(-3.9129)		(4.0265)		**(-5.5659)** *	
4	AAn	1947	1983	1.4504		-1.6048		1.5765		-0.7698	0
				(4.1071)		(-3.9755)		(4.3842)		**(-6.4627)** ***	
5	AA	1957	1978	-0.3589	-0.0267	0.8128		-0.3723		-0.9208	0
				(-1.2808)	(-1.6023)	(1.7026)		(-0.7947)		**(-7.1038)** ***	
6	AA	1946	1996	2.8532	0.0128	-0.7861		-1.2384		-0.7854	0
				(5.9654)	(2.2709)	(-2.9186)		(-3.7882)		**(-6.3885)** *	
7	CC	1946	1992	1.5389	-0.2468	1.5712	-2.2733	0.2573	0.1676	-1.1427	1
				(3.6291)	(-4.1791)	(3.6563)	(-4.4189)	(4.2645)	(2.9500)	**(-7.4221)** ***	
8	AAn	1970	1980	0.8875		0.7055		-0.4995		-0.7588	0
				(4.9494)		(2.6546)		(-1.8585)		**(-6.4086)** ***	
9	AA	1956	1973	5.2555	-0.0384	0.4525		1.1040		-1.0817	1
				(7.6392)	(-5.3543)	(2.5654)		(4.9883)		**(-7.6043)** ***	
10	AAn	1968	1992	-0.2829		0.8367		-0.8563		-0.7573	0
				(-1.9168)		(3.3950)		(-2.6379)		**(-6.3837)** ***	
11	AAn	1950	1956	2.2707		-0.3614		0.2576		-0.5665	0
				(5.7802)		(-4.2513)		(3.6127)		**(-5.8110)** **	
12	AA	1949	1965	3.2460	-0.0401	-0.9328		1.4923		-0.6259	0
				(5.2833)	(-3.0162)	(-2.5208)		(3.2840)		(-5.7401)	

*Notes: TB1 and TB2 indicate expected dates of structural change. In parenthesis, critical t values are reported for the An model; they are -5.51 (1%), -5.07 (2.5%), -4.76 (5%), and -4.42 (10%) – see Perron and Vogelsan (1992). Ann model: -5.86 (1%), -5.59 (2.5%), -5.39 (5%), and -5.15 (10%) – see table A2 by Carrion-i-Silvestre et al. (2004). For model AA: -6.94 (1%), -6.53 (2.5%), -6.24 (5%), and -5.96 (10%) (see table 2 in Lumsdaine and Papell (1997)). For model CC: -7.34 (1%), -7.02 (2.5%), -6.82 (5%), and -6.49 (10%) (see table 3 in Lumsdaine and Papell (1997)). The stars ***, **, and * indicate significance levels at 1, 2.5, and 5 per cent respectively.*

reflect the drought period in the 1980s and the 1990s are 7, 8, and 10, with negative coefficients for the second structural change constant and/or linear trend (in the case of series 7). In the case of series 9 (Piedras Negras), 1956 and 1973 were selected. The second year seems to reflect changes in water flows registered as a consequence of the construction of the 'La Amistad' dam which was inaugurated in 1969.

Generally, dates selected for the years prior to 1950 (specifically between 1946 and 1950) seem to be a consequence of the implementation of the 1944 Treaty. For dates selected in the 1950s and the 1960s, explanations seem to link to the construction of dams which maintained important water flows for agricultural and water supply purposes in big cities located in the zone of influence of the Rio Bravo. Finally, for selected dates in the 1990s, preliminary explanations seem to relate to droughts, given the negative sign that accompanies the tendency coefficient and/or the dummy coefficient that measures the second structural change.

24.6 Conclusions

Following the historical analysis of data for average water flows in twelve measuring points located across the Rio Bravo, this chapter provides both evidence and an evaluation regarding the behaviour of institutions and the framework of water use and allocation in Mexico and the USA. This topic deserves greater attention by authorities in charge of administering the vital liquid, as well as from researchers and scientists, given that certain special circumstances such as drought, overpopulation, and environmental motives may lead to severe bilateral conflicts.

Results obtained from regressions indicate that, generally, treaties and agreements made by both countries on water distribution and allocation have been respected. Although it was necessary to contemplate the possibility of changes that modified water flows throughout the period, estimates indicate that registered water flow changes result from modifications in treaties, construction of hydraulic infrastructure, and periods of drought. Once we controlled for unexpected events, it was possible to demonstrate the stationarity of the data sets, which in practical terms means that in most cases water flows were constant. This constitutes statistically significant evidence that supports the claim that binational norms and treaties regarding water delivery and allocation during the period under study have been respected.

It is not possible to question the efficiency of institutions more recently, when the allocation of surface water resources has seen important reductions on behalf of both nations, as they seem to respond to adverse events – such as drought periods – with negative consequences for the development of the region on both sides of the border. However, in the face of such adverse situations, it is suggested that the legal framework of water allocation be revised in the search for an integral management of the Rio Bravo basin. Regardless, a greater dialogue and cooperation between binational institutions may be of great help in order to solve potential conflicts surrounding water issues.

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25 Determining Spaces for Intervention in a Coastal Basin

Antonina Galván Fernández

25.1 Introduction[1]

The main problem caused by the intensification of agricultural practices is soil erosion created by laminar drag and through sizable landslides. The main cause of the erosion of soil is the destruction of natural vegetation for road-building, housing, industry, commerce, and areas of agricultural cultivation that have slopes of different gradients. Rain run-off produces adverse effects such as an increase in run-off volume, increased run-off peaks, a high presence of sediments and soil nutrients in run-off leading to lower agricultural yields, and landslides.

Coastal lagoons result from the mix of fresh water – from hydrological basins via rivers – and salt water from the sea – through openings caused by tide effects. Given this mixture, biodiversity in coastal lagoons is very high; there are from 50 to 100 species in total, with an average of between 50 and 90 types of molluscs and between 40 and 70 varieties of crustaceans. As well as this, biodiversity is linked to river subsystems such as swamps, marshes, and bogs; these host an important variety of birds, reptiles, and mammals, making them important ecological reserves that keep the earth in balance (Contreras, 1998).

These areas are also amongst the most productive in terms of regional economics, since a significant riverside population depends on them for subsistence. Naturally, these systems degrade rapidly due to sediment formation and low circulation, as well as to unnatural sediments from hydrological basins.

This chapter provides an analysis of the Carretas-Pereyra Coastal Lagoon Basin in Chiapas, Mexico. With an area of 3,696 hectares, it contains continental streams from the rivers Margaritas, Pijijiapan and Coapa and is one of the three main coastal systems in Chiapas. This chapter seeks to determine physical, economic, and human factors linked to the basin, the degradation of the lagoon, and their cause-effect relationship.

The outcome of this work will be a matrix of intervention stemming from the analysis of physical, environmental, social, and productive aspects linked to the basin, based on maps using specialized systems analysis software such as *Geographic Information Systems* (GIS). This chapter provides a solid basis for defining areas of intervention in the basin, framed from the perspective of integrated basin management; this includes the rescue, improvement, and conservation of the lagoon.

Population growth has peaked since the 1970s, especially in the so-called Third World; and it has affected Latin America, including some of the most economically backward countries (Foro Mundial sobre la Soberanía Alimentaria, 2001). The pressure placed on the global ecosystem by human activities such as agriculture, industry, and communications has led to new activities in lands that previously contained undisturbed biotic systems such as forests, jungles, and mangrove swamps. Changing land use in these areas for human projects has increased the environmental impact on the original systems.

Mexico's population grows by 1.6 per cent annually (INEGI, 2005), and this generates at least an equivalent proportional demand for food and services, as well as for land for agriculture and water supply. The country has a total area of 1,964,375 km^2, of which 55.27 per cent is classified as arid and semi-arid regions and only 12 per cent has the characteristics necessary for production; 4.93 per cent is taken up by irrigation districts, 21.87 per cent are seasonal lands, and the remaining 17.92 per cent of land consists of hillsides, which is where 63 per cent of the agricultural producers are located (CONAGUA, 2003).

In terms of weather, the geographical distribution of rain is crucial for agricultural production; the most humidity is found in the south of the country along the coasts, where rainfall is of a torrential kind. In particular, the Southern Pacific coast has between 2500

1 Keywords: Sustainability, basin management, hydrology, erosion.

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and 3600 mm annual rainfall (CONAGUA, 2003), distributed over 6 months. This region also experienced fifteen hurricanes per year on average, which is why 95 per cent of the rainfall is actually accumulated from between 5 and 10 single events annually (CONAGUA, 2008).

Soils in this region are characteristically highly permeable and of variable depth: the result of the combination of the events described above is that when torrential rain impacts on soils uncovered by human activities, the results are significant plate erosions and landslides. Landslides are the most noticeable effects, but they are not the most devastating. Streams take soils and materials and redistribute them along the basin as lateral deposits or on flooded surfaces associated with the streams. These erosion phenomena are perceived as losses by agricultural producers, as soil fertility decreases and producers are forced to use fertilizers. Producers without economic resources must seek new lands to work (Arellano, 1994).

Weather, plants, and soils in a basin are interrelated so that they constitute unique combinations of physical and biological characteristics that make up the environment; also, each combination can assimilate and transfer matter and energy at specific rates, so that each combination represents a potential for productivity. The first step in determining the productive capacities of systems is to define the processes of transference that take place within the basin. This will also allow the impact and dependency relations undergone by their subsystems to be determined.

One of the most important challenges for humankind today is to reconcile survival with the preservation of the environment, given the available land and the pace of population growth. Defining the productive capacities of the basin is the basis for making decisions about the exploitation of the system; the goal of this is to maintain production rates over the long run.

25.2 Justification

Currently, we face a fundamental contradiction. We have to share our nurture with thirty million species on the planet and at the same time our culture and production model insists that the world should exclusively service human needs. In this context, illness, economic convulsions, environmental degradation, and resource scarcity are the platform for conflict between different social groups who inhabit the same geographical space. This leads to poverty, social exclusion, marginalization, economic instability, and rivalry in appropriating existing natural resources, as can be seen in Mexico.

To meet this situation, an outlook that emphasizes the integrated management of natural resources will encourage attempts to maintain the exploitation of resources at a constant level and over an indefinite timeframe, but resources are finite and their permanent exploitation is a contradiction. Sustainability has limits which depend on the physical environment, and it is imperative for resource managers to establish the limits of their activities as imposed by the environment. Exploitation of resources should be planned according to the real capacity of the environment to generate them. To do this, a detailed evaluation of the system needs to be undertaken to determine 'what' is really available for exploitation (Alier/Roca, 1994).

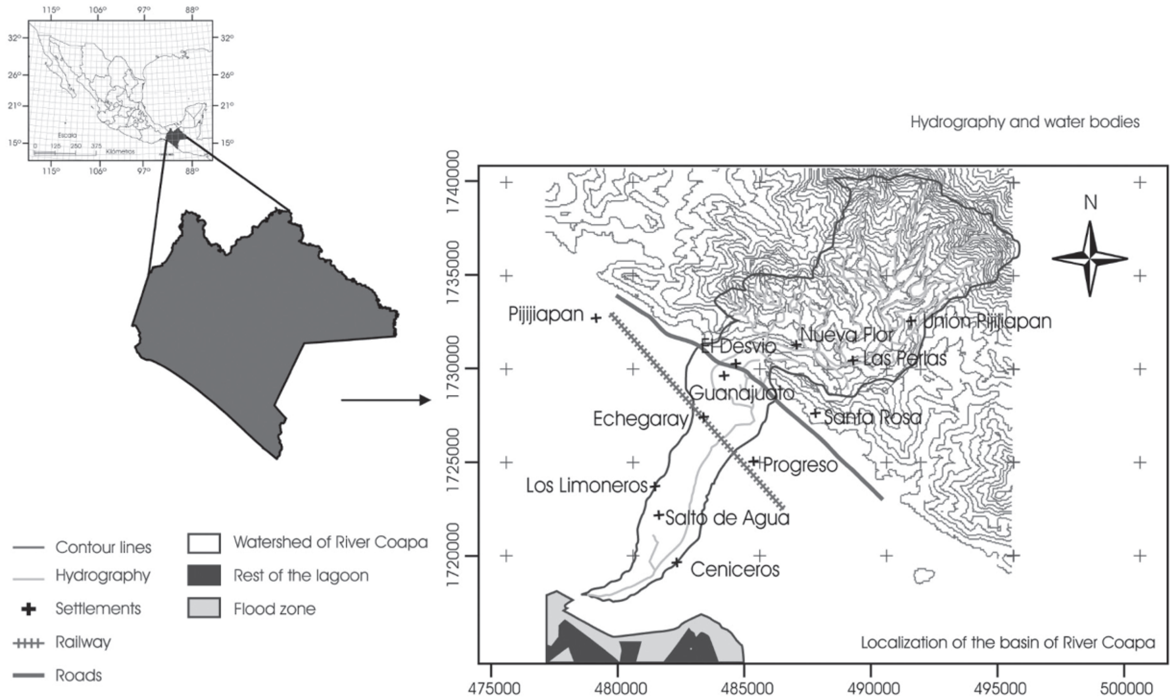
The objective of this study is to evaluate issues relating to water, soil, and agriculture in order to shed light on the problems and to offer decision-makers a planning tool. This will include a description of the physical environment, of management and demands by producers, and of the interaction between the different components of the system; this can then be an initial diagnostic tool for determining available water volumes and fractions in the basin related to each element in the hydrological cycle. The evaluation uses *Geographic Information Systems* (GIS), a tool that offers a new outlook for relating hydrometric data to geographical spaces and so enabling spatial analysis.

25.3 The Study Area

The coast of Chiapas comprises a coastal strip of 270 kilometres in the Pacific Ocean. It has an exclusively economic zone of 87,954 km^2, a continental platform of 11,734 km^2, and 75,828 ha of lagoons and marshes. In this zone is the Carretas-Pereyra lagoon system, a part of the municipality of Pijijiapan, with an area of 641 km^2 including tributary rivers and sea estuaries (SARH, 1975). The rivers Margaritas, Pijijiapan and Coapa are the main outflows, and the Coapa River Basin is a typical example of a coastal basin system feeding the region's lagoon (figure 25.1).

The coastal zone consists of a floodplain and a series of lagoons and marshes that are interconnected by a canal system. The lagoons were highly productive for fishing until 1992 (Contreras, 1993), with seafood such as shrimps and oysters, and some economically profitable fish such as mojarra (Gerreidae), catfish, etc. This productive process has supported the life of

Figure 25.1: Location of the study area. **Source:** Data from author's research.



the inhabitants who have settled on the coast and on the lagoons since pre-Hispanic times. On the continental side, the river Coapa has an annual average minimum flow of 5 m^3/sec, with historical peaks of up to 160 m^3/sec (CONAGUA, 1995), although it has recently experienced episodes of drought. This basin demonstrates extreme behaviour due to its geographical position; it is located in the most humid region of the state and has rainfall of over 2500 mm/year. These results from the physiographical conditions of the region, which include high pendants and short transverse sections over highly permeable soils of superficial depth that make for a rapid and very strong torrential run-off. Nevertheless, during the dry season these streams become sporadic over most of their course (Galván et al., 2001).

Regarding agricultural production, 60.3 per cent of the region's agricultural land consists of small units of less than 5 hectares and/or an ejido-communal system; 84.63 per cent of producers receive support and subsidies for agricultural production from the federal government. About 1.15 per cent of the cultivated areas have an irrigation system, and 54.23 per cent rely on seasonal rain. Only 0.05 per cent present some degree of technological development, more oriented towards agricultural machinery than towards the irrigation systems, with 0.12 per cent practising organic agriculture, especially coffee (Galván, 2003).

Water is exploited from both coastal and continental systems. In the higher basin it is used as a surface resource for small land parcel irrigation, as potable water, and for sanitation in some communities. When it reaches the coast, its dominant phase is as a ground resource; around 30 per cent of run-off infiltrates to form a free aquifer of average potential, which means that water volumes fed into the lagoon are not only on the surface, but also, and mostly, underground. In this region the National Water Commission exploits the aquifer to provide potable water for communities along the coast. This extraction reduces the ground recharge rates. In terms of surface water recharge, following rectification and desilting works undertaken since 1975, water transference rates to the lagoon have decreased, reducing the infiltration into the aquifer. The remaining course is used for sanitation in coastal communities; it reaches the lagoon with an intact charge of pollutants (Galván et al., 2001).

Additionally, extreme rainfall from September 1998 increased sediment rates and in a single event the lagoon and its branches were silted up, modifying the bathymetric configuration and the distribution of streams and sediments; currently, the depth of the lagoon and headlines is less than 30 cm. This is a serious problem which has considerably decreased storage capacity, and together with nutrients and agrochemicals from agricultural land run-off and discharge of human pollutants has affected species and overall balance in the lagoon (Marquez, 2001).

25.4 Research Methodology

Using numeric modelling in a variety of fields is nothing new; mathematical models have always been used because of their predictive value. This methodology requires a considerable volume of time-dependent hydrological, geomorphological, land use, and physiographical information. This information needs to be detailed and of high quality, and to represent actual evaluated conditions as closely as possible; it also needs to represent observations of the control model variables over time in order to establish its capacity for adjustment (Dumanski/Pieri, 2000).

Decision-making models are divided into several types. Rigid types associated with mathematical models stand out, based on the selection of a variable as the axis, and the selection of the variable's threshold value in order to be able to consider an action as positive or negative – action that can range from regressions to neural networks. The other type of models establishes variables and hierarchies according to information from an expert, and the types range from hierarchization to multidimensional models. The latter depend on the experience and specific knowledge of experts, making them highly subjective; they are based on the definition of relevant variables for phenomena that can be positioned relative to each other in the system (Callas/Kerzee/Bing-Canar, 1996; Mohan/Shearer, 1995).

In the environment, we find thousands of organisms that base their system of organization and efficiency on the systematic repetition of a well-defined basic structure. This is the case with the organs of a living being, where the cell is the basic structure that repeats itself with minimal variations; this is what makes it a specialized entity. The mathematical base of fractals is similar: we are dealing with distributed repetitions of exact copies of a base function which are linked by a time lapse or displaced in space in such a way that the last numerical evolution of one system becomes the start of the next. A complex form of this mathematical construction occurs when the copies of the base function are not exact, with some of its variables altered so that the exit-point numerical evolution varies in terms of spatial distribution. However, changes are finite for each variable, so that when all possible changes (n) that a variable (k) may have undergone have been considered, we return to the initial point or value of the function. This means that each copy of the topic maintains all the base information, and this allows us to recover the original information at any level; the same thing happens with the genetic information of cells. This capacity of simple systems to transform into complex systems maintains the base information as an isomorph. The process just described is known as a 'loop'; a loop is produced when an ascending or descending system of extension m is established in such a way that after an interval of k repetitions we reach the departure point once again (Hofstadter, 1987).

Another way of expressing this would be: moving upwards or downwards through the levels of a directed hierarchical system composed of simple bound elements, it is possible to produce subsystems that repeat themselves, and are defined as recursive, and from which it is possible to obtain the base information of the entire system.

Linking this with the analysis of a water basin, and even going beyond this in order to establish an Integrated Basin Management System, this approach offers a good platform as we are dealing with complex, self-contained, and recursive systems. We also propose an initial characterization in order to establish the reference framework; a starting point for any management plan. Establishing the cause-effect relations under directed hierarchical systems, we implement the loops that contain the basic elements that permit numeric evaluation with finite changes to the variables; all these together generate the total basin space (Galván/Márquez, 2006).

Given the salient characteristics of a basin, it is possible to divide it into simpler subsystems that maintain the original structure of the complex system (sub-basins), which share the total information of the basin but are differentiated by finite variations in space. Each sub-basin is defined from the combination of factors such as physiography, geology, soils, weather, and vegetation which make a subsystem unique in its specific traits and rates. However, it is also possible to establish the cause-effect relations between factors that define the sub-basin and to make these the base of information retrieved (variables). In this way the approach, analysis, and evaluation of the subsystem enable us to construct a unique reference framework for each sub-basin with an application and replication that is valid for all other basin components (Galván/Márquez, 2006).

Finally, once the subsystems that make up the basin are identified, and the cause and effect relations together with the quantifiable variables are established, it is possible to express the base information in management plans and to account for social factors. In this way, the action-reaction scenarios of suggested actions for management of the basin can be established (numeric modelling), i.e., the system information is recovered. Phenomena present in a basin that condition its productivity are strongly interrelated, and they are too complex for rigorous deductive analysis; in some cases they present random components that are not well-defined enough to be treated statistically. In fact, biological systems making up the basin present the problem of a high time dynamism. Whereas physical problems are easily quantifiable and stable in time, social systems are hard to quantify and they are highly dynamic in time (Clayton/Radcliffe, 1996).

Applying the concept of *loop* to the divergent agents that interact in the basin – physical, biological, and human environment – brings us to a universe of information that is itself composed of different interlinked and quantifiable factors (variables) in such a way that monitoring a part of it allows us to obtain the bigger picture of the whole universe. Furthermore, the combination of universes generates a unique scenario, hard to replicate exactly, but with enough similarities with the other sub-basins that make up the basin. This generates methodological principles for making inferences regarding actual and probable interactions between the systems under study (management of planned scenarios; Galván/Márquez, 2006).

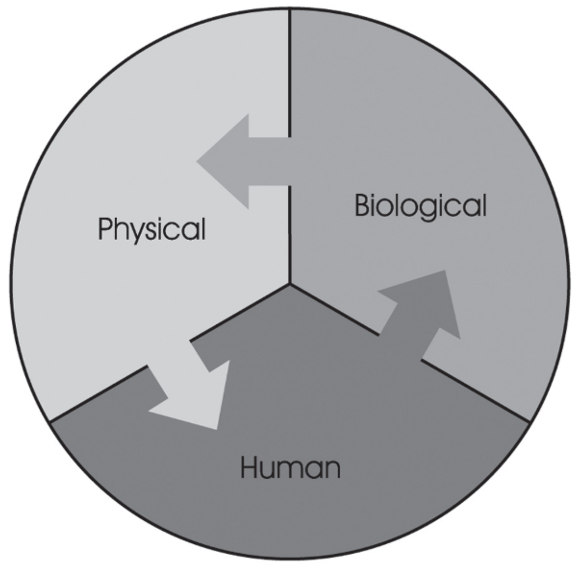
The systemic approach claims that relations between the components of a system require that phenomena studied be large-scale and in some cases contain a random element; these are defined as second-order relations. On the other hand, the internal relations of the components (variables) require phenomena to be well-defined and unidirectional in space and time, and these are defined as first-order relations (Ochoa, 1997). In the case of basins, the schema put forward in figure 25.2 represents the three universes at the base of the system, with a unique exit to the other universes which constitute second-order relations.

For each universe, we have identified the factors that contribute to it and its numerically quantifiable relations. These are sometimes multiple and they are not necessarily unidirectional (figure 25.3).

It is possible to say that each universe is composed of a number of interrelated factors that have the following three properties:

1. The properties or behaviour of each universe have an effect on the properties or behaviour of the entire basin; these effects are hard to define and quantify. This property defines second-order relations.
2. The properties and behaviour of each factor and the way in which it affects the whole depends on the properties and behaviour of other factors in the same universe and/or another universe, and operates as a link between both. This means that there are at least two factors directly interlinked, with quantifiable and established functions, and thus no part has an independent effect over the whole. This property defines first-order relations.
3. All factors in the universe present this past property, meaning that each one of them has a direct relation with another variable, and none is independent of the whole. Thus, the factors in a basin cannot be analysed in terms of independent universes or relations (Hofstadter; 1987).

Figure 25.2: Universes and factors that make up the basin.
Source: Author's research data.



Splitting a complex problem into smaller units that can be dealt with separately under a single type of analysis and discipline is based on the definition of first-order relations which are quantifiable by direct measuring (numeric modelling). This enables us to extrapolate them under controlled conditions. In order to define second-order relations, the complex system is divided into smaller subsystems that group simple and strongly interlinked problems; cause-effect relations are defined from one subsystem to another, and not as variables. Hence a multidimensional structure is generated, into which important amounts of information from different domains are integrated.

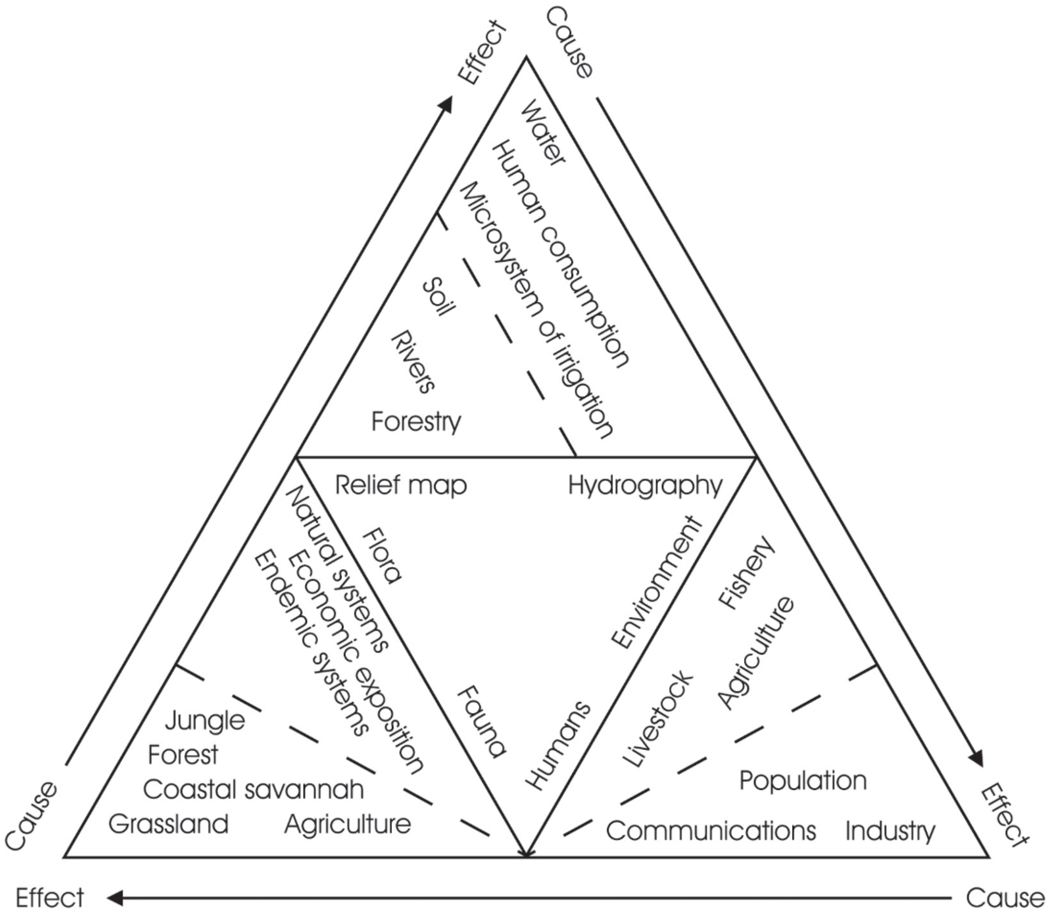


Figure 25.3: Relations between the factors that constitute the universes. **Source:** Galván and Márquez (2006: 318).

This establishes the cause-effect relations for each system, and results in a loop structure (figure 25.4).

To select and use a model that correctly simulates all the variables involved in basin management – where the physical environment and human demands are taken into consideration – we first need an in-depth knowledge of the physical processes and their cause-effect relations in order to determine its production and regeneration. Secondly, we must be aware of the economic-productive activities that represent the survival needs of the population, such as a basic supply of food and water from the environment. The establishment of a hierarchy that is capable of being analysed, in which subjective elements are identified and both physical and productive universes are linked, is the basis for an integrated basin management. One way to do this is by generating a series of indicators for each space, which can be combined at a later stage by means of a decision-making model, which will define actions to be taken based on the variables that are significant for each universe (planning system; Eastman et al., 1995; Charlene/Michael, 1996). Following this approach, the first task is to delimit each space and each cause-effect relation.

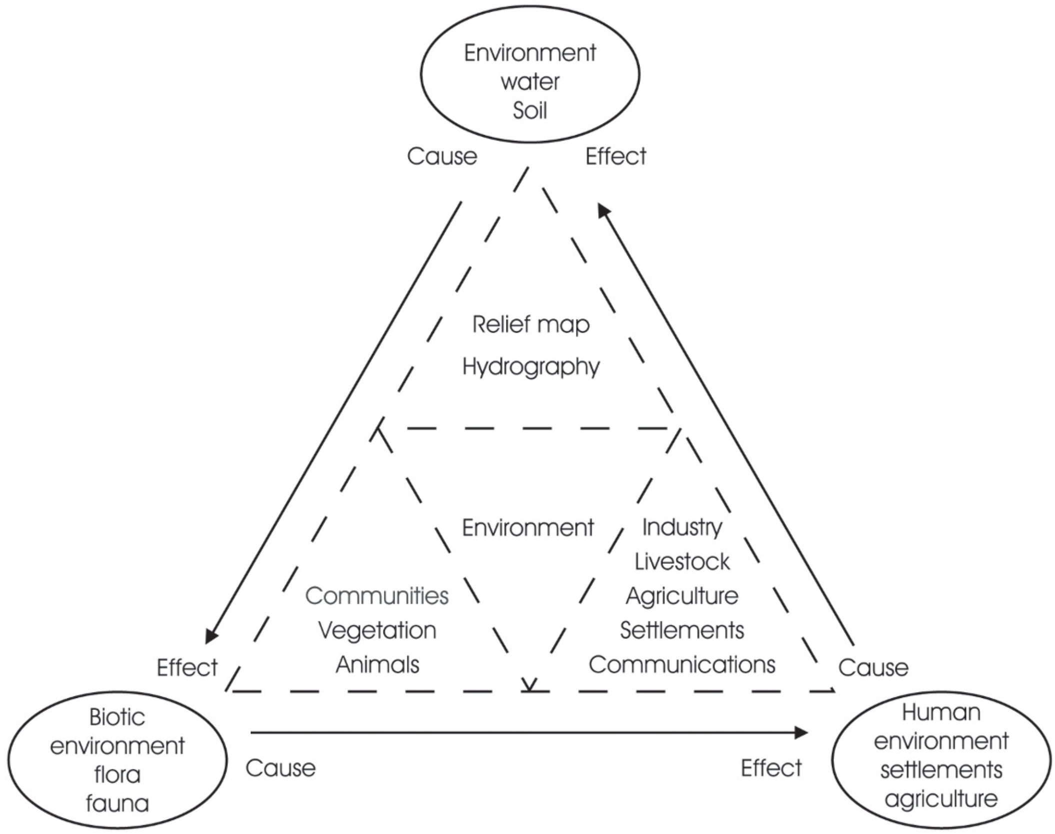
In the social sciences, the methodology of *principal component analysis* (PCA) consists of generating social (numerical) indicators from qualitative variables. Basically, this is a model that correlates spatially distributed data with known functions; the generation of an indicator using this concept requires that we define the 'weight' of each observed variable in the model. This is expressed as:

$$IN_j=A_1X_1+A_2X_2+\ldots+A_nX_n \quad (1)$$

where
IN_j= value of the indicator associated with the subsystem *j*
X_i= observed variable
A_i= weight (importance) of the variable in the model

Here, the sum of the coefficients is unitary and is part of the hierarchy in such a way that the value of each coefficient represents its 'weight' in the space ana-

Figure 25.4: Loop that links the components of a basin. **Source:** Galván and Márquez (2006: 319).



lysed. This function is known as the *Empirical Orthogonal Function* (EOF). It generates a coefficient space (base space) where variables are located by 'weight' within functional relations, so that those with zero impact are signalled. If researchers conclude that a variable 'does not add to the model', it does not mean that it is irrelevant, but instead that possibly this variable is part of another variable. With this approach, it is evident that the model will be modified and that some of the variables – if they lose their significance – will simplify information requirements (Charlene/Michael, 1996).

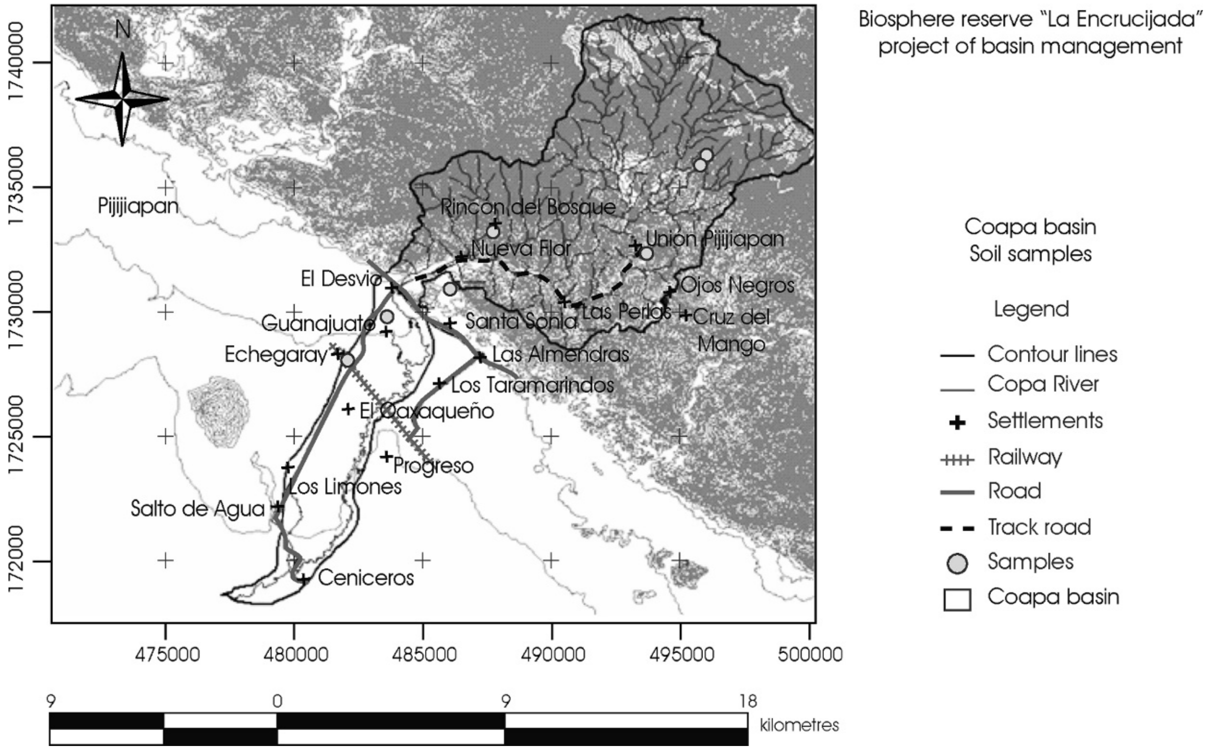
25.5 Results

An evaluation of physical, biological and socio-economic systems was undertaken. Changes in vegetation were reviewed; agricultural zones and their spatial distribution were identified; the hydrological cycle was examined; and soils were characterized. Data regarding productivity and agricultural practices were collected and were associated with the different socio-economic environments of the basin. With this information, a micro-regionalization of the basin was undertaken, and productivity indicators for each micro-region were generated, as well as a matrix of proposed activities. This matrix was presented to different groups of agricultural producers so that they could prioritize their demands. This became the matrix of intervention.

25.5.1 General Considerations

The basin of the Carretas-Pereyra coastal lagoon covers seven communities: Guanajuato, Coapa-Echegaray, Salto de Agua, Las Perlas, Nueva Flor, Unión Pijijiapan, and Ceniceros. It has a total area of 164.43 km^2 and a total population of 1,936 inhabitants, representing 0.06 % of the total population in the state of Chiapas. There is an average of 5.45 inhabitants per household, 89 per cent of houses have electric energy, 9.54 per cent have tap water, and 55.41 per cent have sewage. However, 22.67 per cent of the population is illiterate and 60.79 % is literate. The main economic activity is agriculture, although populations close to the coast also fish (Galván et al., 2001; IDSM, 1998; INEGI, 2001, 2004).

Figure 25.5: Topography. **Source:** Morón Vázquez (2004: 34).



25.5.2 Physiography

The area researched is located in the Sierra Madre in Chiapas and on the coastal plain to the south of the Macizo Chiapaneco – a mountain range extending from north-east to south-east with average heights of 2,000 metres. The Sierra Chiapas and its high mountains constitute a long and wide range tending in the same direction; water streams in this region display dendritic patterns, whereas water on the south-east side flows towards the Pacific in streams that run into estuaries and lagoons along the coastal region.

25.5.3 Topography

The topography in this region is mainly formed of two zones; the first is a 25 km strip that descends from the mountains to the coast, where plains predominate as well as concave slopes and a few depressions. It has only one outflow, and because of the accumulation of marine and terrestrial sediments, it becomes a floodplain. In the higher area we find the Sierra Madre of Chiapas, reaching a height of up to 2,300 metres, with slopes of up to 35 per cent gradient. Concave ravines predominate throughout the valleys, with a highly bifurcated dendritic outflow, as can be seen in figure 25.5.

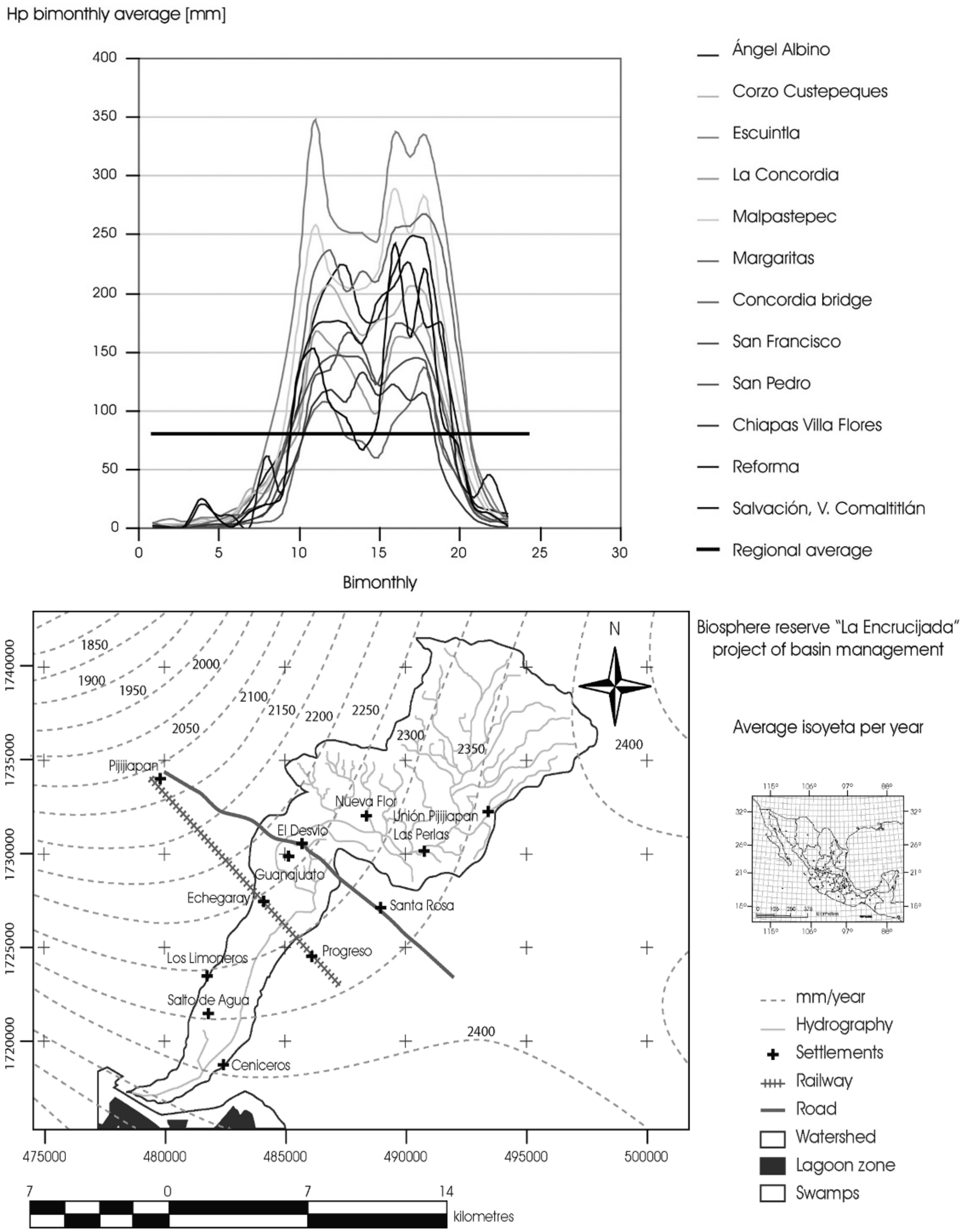
25.5.4 Weather

There are three weather types associated with physiography: Am (*warm humid*) A(wz) (*warm subhumid*) and Acm (*mildly warm and humid*). The predominant weather characteristic is humidity, with annual rainfall of above 2000 mm/year, and dog days (canicule). Average yearly temperature is 27.7 ºC, with maximum temperatures of up to 38 ºC and minimum temperatures of 18 ºC (Galván et al., 2001). The dry season lasts from November until April and has less than 10 per cent of the average yearly rainfall (h_p) and an average fortnightly rainfall of 80.04 mm. The rainy season starts in May and lasts until October; it displays torrential behaviour (figure 25.6).

25.5.5 Soils

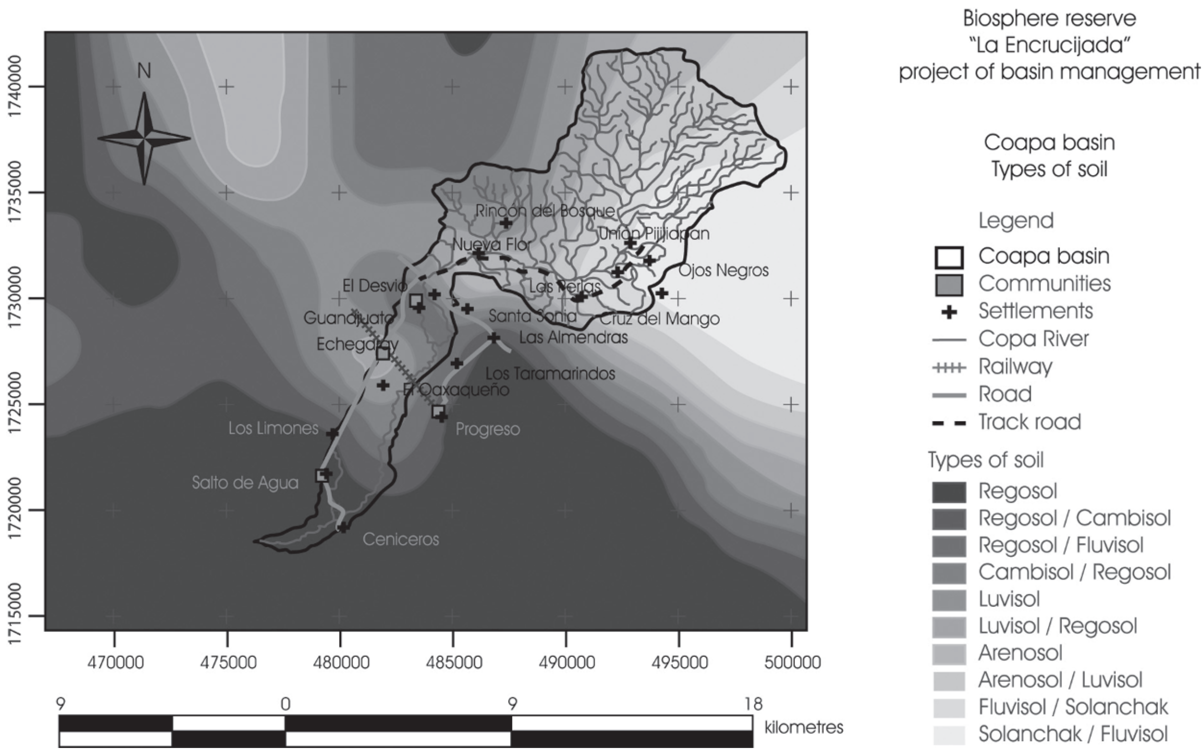
The predominant soils are clay and sand of granitic origin, originated by weathering and deposition of material from the Sierra, combined with extrusive igneous rocks, except for the regions close to the coast which present a combination of deposits. The most

Figure 25.6: Fortnightly histograms, rain distribution. **Source:** Ulloa Juárez (2005: 41).



important components according to INEGI's soil chart are lithosols, regosols, solonchaks and to a lesser extent luvisols as well as secondary units such as fluvisols, gleysols and regosols. The texture class varies according to the zone. In the Sierra, middle textures predominate, whereas thick textures predominate in the plains and fine textures near the sea (see figure 25.7).

Figure 25.7: Soil distribution. Source: Pérez Hernández (2006: 58).



25.5.6 Hydrography

The Coapa River has many minor tributary streams, with a dendritic outflow pattern of order 4, which gives it a good hydrological response to any rainfall event; the current index is 0.153 km/km^2. These patterns are representative of a rapid outflow system and of high run-off peaks. Also, time concentration is 2.75 hrs, a relatively short time lapse. It is a system split into two parts: the high basin has a very high efficiency rate in terms of water concentration and run-off, whereas the coastal zone with slopes of less than 7.5 per cent gradient has low concentration and flow rates, with a low run-off potential which accounts for recurrent flooding despite low-magnitude rain events.

With a low run-off trend, annual oscillation rhythm is constant, so, making an annual calculation, we see an important decrease in annual registered volumes. It is important to emphasise that the monitoring station is located in the transition zone between the high basin and the coastal zone. Additionally, since 1986 the monitoring station has been relocated at 500 m below its original position. One can also observe that peaks higher than 100 m^3/sec repeat regularly – every seven years – and they can thus be associated with global weather phenomena such as the Niño effect (Galván et al., 2001).

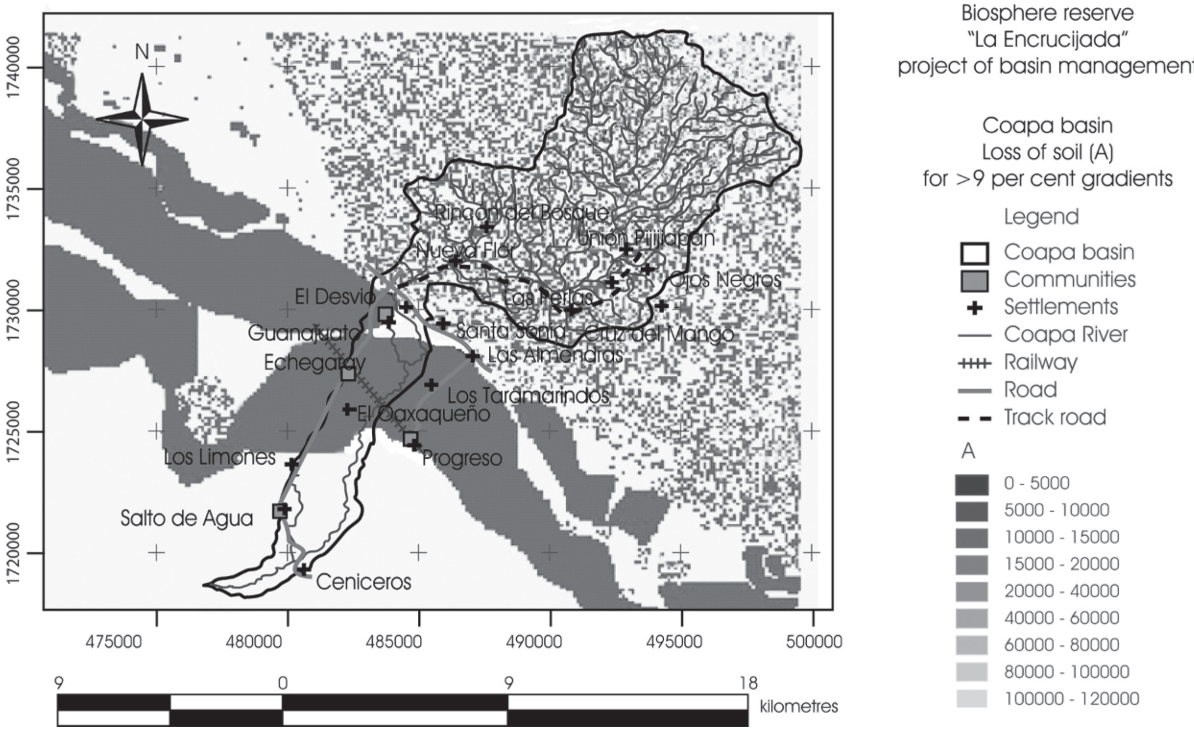
25.5.7 Erosion

Erosion rates vary between 25 and 2,500 tons/ha/year. We can see that the main erosion areas are the regions with slopes of between 1 and 5 per cent gradient, corresponding to the plains where agriculture takes place. Next, we find erosion on slopes of between 5 and 10 per cent gradient, in zones near rivers, where the land starts to rise towards to the Sierra. Finally, slopes higher than 25 per cent gradient still have efficient groundcover. There is a region of crushed stone distributed from the middle basin upwards, which coincides with the steepest zones. Thus, the determining factor of erosion in this region is its physiography (Galván et al., 2001; figure 25.8).

25.5.8 Vegetation

Forests, jungle, and mangroves predominate, representing the primeval vegetation. However, humans have introduced commercial species such as subsistence grains, fruits, and grass for cattle. Agriculture is small-scale for local consumption; corn is the main

Figure 25.8: Potential erosion**. Source:** Pérez Hernández (2006: 62).



crop together with some grains such as beans and lentils, and basic vegetables such as tomatoes, chilli, squash, and peas. The latter are cultivated in small domestic parcels of land, in the backyard. Besides this, there are fruits such as melon and watermelon. Perennial fruits such as mango, tamarind, and avocado have a decorative or protective function, which is why they have different agriculturally-specific husbandry practices. Each agricultural producer has 1.6 ha on average. With regard to corn, all producers get support from PROCAMPO; 15.3 per cent of the basin is used for this activity (SAGARPA, 1999, 2000, 2004). These resources are used for the purchase of seeds, fertilizers, and herbicides in the two cycles of spring-summer and autumn-winter. The seeds that are used are native; they are obtained from the harvest. Some producers use enhanced seeds; average yield per hectare ranges from 600 kg using native seeds up to 800 kg with enhanced seeds, depending on the soil and on seasonal weather conditions (Galván et al., 2005; figure 25.9).

25.5.9 Micro-Regionalization

The basin has been divided into five regions (Galván, 2003): high basin, middle basin, lower basin, floodplain and wetlands (figure 25.10). Of these subsystems, only three are populated, the middle and lower basin and the coastal plain; the remaining two cannot be cultivated as they are ecological reserves.

25.5.10 Productive Systems

Data collection regarding productive information was undertaken by direct survey. This information was important for characterizing the parcels of land. Overall, 12 surveys were undertaken in three different localities, applied to different producers. The information obtained is summarized in table 25.1.

According to the data that were collected, three forms of resource exploitation were found: direct, indirect and extraction. Table 25.2 shows the resource exploitation for each subsystem.

Following on from this data, the subsystems can be classified using binary criteria in order to assign overall grades (Carle/Fogg, 1996; table 25.3).

After completing the matrix, the *Empirical Orthogonal Functions* (EOF) methodology can be applied, giving us the impact indicators for each subsystem (Galván, 2003; table 25.4).

According to these results, most resource exploitation occurs in the middle and lower basins, in the ‘soil’ sector. Furthermore, based on surveys we can see that the lack of technical assistance in land parcel management is the determining factor leading to this.

Figure 25.9: Distribution of vegetation. **Source:** Galván (2005: 27).

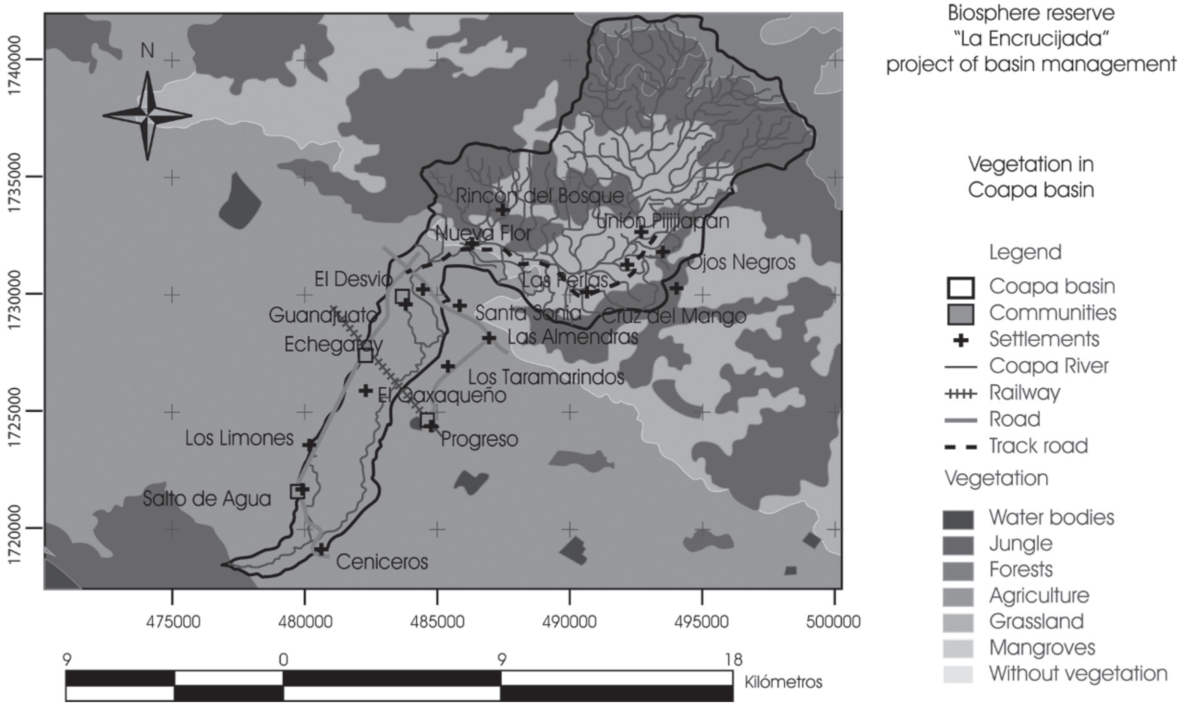
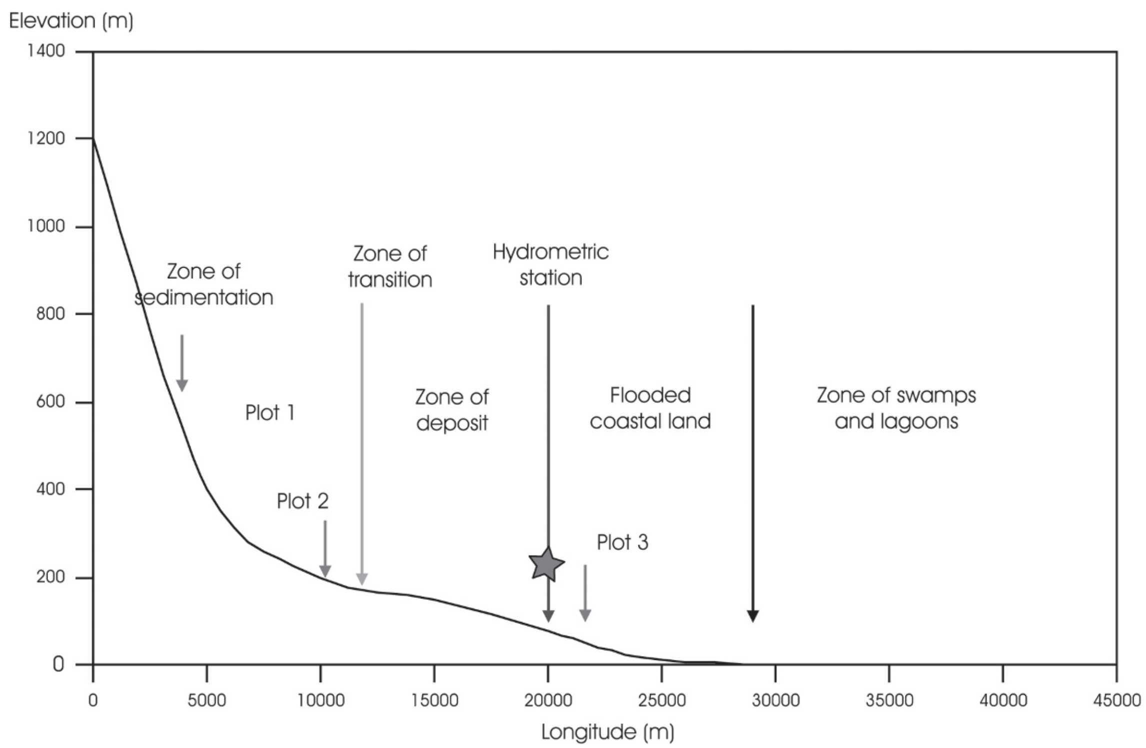


Figure 25.10: Basin subsystems. **Source:** Galván (2003: 14).



In the high basin, the plain, and wetlands, exploitation is lower because the recommendation for these areas is that works be oriented towards conservation. Based on this information, the intervention matrix for each subsystem can be obtained (table 25.5; Galván/Márquez, 2006).

Table 25.1: Types of producers. **Source:** Data from author's research.

Locality	Area of Productive Unit	Main product	Land tenure	Type
Nueva Flor	10.25 ha	Corn	Mixed	Medium diversified
Coapa Echegaray	2.5 ha	Cows	Small private property	Small monoproducer
Guanajuato	3.5 ha	Vegetables	Ejido lands	Average economic

Table 25.2: Exploitation by subsystem. **Source:** Data from the author's research.

System definition		**Exploitation by the population**				
		High basin	**Middle basin**	**Lower basin**	**Floodplain**	**Wetlands**
Soils	Direct	Without use	Seasonal agriculture	Seasonal agri-culture	Seasonal agriculture Irrigation agriculture	Without use
	Indirect	Without use	Livestock	Livestock	Livestock Flood protection	Flood protection
	Extraction	Without use	Without use	Building material	Building material	Building material
Vegetation	Direct	Wood (furniture, firewood) Medicinal plants (foodstuffs)	Wood (furniture, firewood) Medicinal plants (foodstuffs) Fauna to eat	Plants (medicinal, foodstuffs) Fauna to eat	Wood (firewood) Plants (medicinal, foodstuffs) Fauna to eat	Wood (firewood) Plants (medicinal, foodstuffs) Fauna to eat
	Indirect	Decorative plants	Decorative plants	Decorative plants	Decorative plants Fauna for sale	Ecotourism
	Extraction	Protected fauna (illegal)	Protected fauna (illegal)	Protected fauna (illegal) Fauna for sale (lobsters)	Protected fauna	Fishing, shrimps, molluscs
Water	Type of use	Without use	Direct point (rustic well) Spring water col-lection	Rustic wells (water wheel) Deep well (CONAGUA, private) Direct supply from the river	Rustic wells (water wheel) Deep well (CONAGUA, private) Direct supply from the river	Fishing
	Exploited body	–	River and streams	Aquifer River	Aquifer River	Lagoon
	Use	–	Agricultural irri-gation Domestic Sanitation	Domestic Agricultural irrigation Sanitation Potable water	Domestic Agricultural irrigation Sanitation Potable water	Commercial fishing
	Quality	Good	Below official standard	Below official standard	Below official standard	Below official standard
	Availability	—	River and stre-ams	River	River and lagoon	Lagoon

Finally, table 25.6 shows a series of intervention alternatives that are distributed according to the different sectors that make up the basin, oriented towards the characteristics of each specific sector. Each square represents one of the subsystems; crop cultivation and

Table 25.3: Grades of the human environment. **Source:** The author.

System definition	Basin				
	High	Middle	Low	Floodplain	Wetlands
Soils	0	2	3	5	2
Vegetation	7	8	6	7	8
Water	0	9	13	14	11

Table 25.4: Indicators of impact. **Source:** Galvan (2003).

Variable	Basin		
	High	Middle	Low
Soil	0.0000	0.7582	27.8500
Vegetation	1.1400	4.1620	50.0500
Water	0.3074	0.2181	32.8600

management alternatives are selected according to water availability, including fruit trees.

25.6 Discussion and Concluding Remarks

Currently, the basin has been almost totally opened up for agricultural production; approximately 80 per cent of the area, including slopes with gradients greater than 35 per cent. The main activities represented are livestock, seasonal agriculture of basic crops for subsistence (corn and beans), and some fruits and vegetables for the local market and for local consumption. Traditional productive practices, such as the use of slash-and-burn agricultural practices, affect the regeneration of native vegetation and soil quality. Lately, community efforts have begun in order to stop this practice, although most remaining productive practices have a high environmental impact.

The combination of physiographical factors in the basin and productive systems used by the population has resulted in processes that are degenerative for the physical environment, and this is reflected in a constant and unrecoverable loss of productivity. Losses in fertility are mainly the result of weathering, landslides, silting, and deposits of waste materials in bodies of water, especially in the lagoon. Production levels have been maintained by means of opening new lands for cultivation and by intensifying the cycles of cultivation (reducing rest and rotation periods). The other action that would focus on alleviating loss of fertility would be to confront extended and indiscriminate use of agrochemicals in the whole production process, from preparation of the land (defoliation, pesticides) up to life support for the plants (fertilizers, growth hormones, etc).

Suggested alternative management schemes are based on the physical and biological conditions for each of the subsystems identified in the basin, given the necessary inputs for each crop. Thus, proposals tend to be very rustic, with natural fertilizers, conservation farming and multiple use of land parcels. At this stage it is vital to highlight the use of organic fertilizers such as compost, manure, and green and natural waste to replace agrochemicals. In order to reduce erosion, suggested strategies include agronomic practices (conservation farming) and ground cover management (Eswaran et al., 2000).

The productive economic unit has been identified as the family, which is taken as the basis for multiple management proposals, for example for forestry and forest-farming systems. Another important management proposal is the annual calendar where workloads should be distributed throughout the year, guaranteeing a permanent income for families.

Potential crops were identified for different seasons throughout the year, taking into account the dry season and the availability of water; only chilli and squash can be cultivated in parcels of land smaller than two hectares. Availability of water is the main barrier to production, so increases in the area of land cultivated do not guarantee a fixed and sufficient income for the extensive producer. The most recommendable option would be intensive cultivation systems, given their capacity to retain energy, re-circulate water, and bear high production loads; they yield 4 to 6 times as much as extensive systems. However, technical assistance, heavy initial investments, and the search for specific markets for products would be a precondition for these.

Given the availability of water in the basin, corn is not a sustainable crop for the region. The proposal is to exclude it from productive activities, and to seek viable alternatives which would generate enough profit margin to enable corn to be imported to the region. Lastly, for commercial crops (fruits and vegetables), local and regional markets should be explored to establish potential market niches. However, bearing in mind that the main objective is the subsistence of the production unit, management of minor livestock and birds is restricted to the backyard.

Table 25.5: Intervention matrix for each subsystem. **Source:** Galvan et al. (2006: 713–739).

Variable	Subsystem				
	High	Middle	Low	Floodplain	Wetlands
Soil	Non-intervention	Gardens	Conservation farming	Conservation farming	Non- intervention
Vegetation	Control of agricultural border	Management of acahuales (native flowers and plants) and forestry	Pastures	Restitution of vegetation	Non- intervention
Water	Non- intervention	Monitoring and control of water collection	Discharge control	Discharge control Groundwater monitoring	Non- intervention

Table 25.6: Suggested alternatives. **Source:** Data from the research of the author.

	Management	
Subsystems	High	Control of agricultural border Reforestation Management of acahuales (native plants and flowers) and forestry
	Middle	Gardens: For example, the parcel of Luis Lara Avendaño is highlighted, crop types are radish, coriander, chilli, squash, cucumber, mango Small parcels with irrigation, no-till farming and natural fertilizers Management of acahuales (native plants and flowers) and forestry Minor livestock in acahuales and parcels Monitoring Control of water collection (for example, in the parcel of Albertina Ramón Camper)
	Low	Conservation farming (the communal parcel of Marcos Tonala Lando is highlighted with crop types: squash, corn) Management of cover plants, natural fertilizers and reincorporation of residues Pastures (for example, the parcel of Ramón de Los Santos) Parcel rotation and crop combination, incorporation of residues, and grass type variations. Understorey implementation, reforestation of ravines and management of family parcels Discharge control monitoring (for example, SD parcel)
	Plain	Conventional farming of corn, sorghum, beans and sesame; rotation of high-yield fields with natural fertilizers, integrating stubble as livestock foodstuff Restitution of native vegetation, minor livestock in acahuales Forestry Discharge control and monitoring
	Wetlands	Without intervention

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26 Social Intervention as a Practice of Translation: Sustainability and Processes of Community Knowledge

Claudia Rocío González Pérez and Antonina Galván Fernández

26.1 Introduction[1]

Currently there is a new relationship between agents producing traditional knowledge and new actors such as businesses and intermediary organizations, who constitute what Castells (1998) called the 'knowledge society'. Present trends which guarantee that knowledge is really assimilated by the individual recognize that the cognitive process involves four steps: acquisition, comprehension, internalization, and appropriation. Regarding environmental education, this new strategy of instrumentalizing knowledge seeks for individuals to internalize the concept of 'sustainable management', to establish new relations with their environment, and to gear their personal actions towards the management and conservation of the ecosystem and the community.

Sustainable basin management depends not only on expert knowledge and available information but also on the involvement of the populations settled in the basin; it needs to take into account their traditional practices and dynamics, their way of preserving water resources, and their economic and social development, currently one of the main obstacles in most Mexican communities.

The strategy to follow is to link the problem with the instrument as well as with resources and then to specify actions so as to establish an action plan that matches the social structure of reality; a problem does not exist if it is not addressed in terms of the people that face its consequences. Thus, an action plan derives from the construction of a problem following an exercise of cognitive interaction and the generation of a common, local, and interdisciplinary language. From this we can now focus on the actions that might act as problem solutions or as preventive strategies.

This work presents a methodology for generating action plans that integrate agents in the basin; they are the most suitable actors, given their knowledge and experience. Also, it is important to account for available resources when taking specific actions, i.e. the kind of existing material and immaterial resources, and those that come from the authorities, other agents, and/or knowledge generated at local level in the community itself.

Currently, there is a new relationship between traditional agents of knowledge and other emerging agents such as businesses and intermediary organizations. These new elements make up what Castells (2006) calls the 'knowledge society'. His idea is rooted in the conception that nowadays knowledge is socially distributed and is generated in a context of concrete problem resolution by the various actors that make up a community. It follows from this vision that *integrated participatory programmes*, encompassing different outlooks on a single problem, are generated and put into practice by the government for community development.

Thus, the individual receives information – via marketing – directed to specific interests that manifest themselves at all levels of everyday life: visual, direct, and body language, as well as subliminal materials that address needs and habits. On the other hand, formal education is limited in so far as it requires restricted times and spaces to 'present concepts' for the gradual assimilation of knowledge; here, tools are strongly related to visual content and they are frequently not linked to the everyday life and technology of individuals. Again, current education trends state that in order for knowledge to be assimilated by individuals, we need to recognize that the cognitive process has four steps: knowledge *acquisition, comprehension, internalization, and appropriation*. These trends also recognize that the process ought to be supported by tools rather than by abilities – given that different individuals have different ways of approaching

1 Keywords: Sustainability, basin management, knowledge webs, socio-economic performance.

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reality – emphasizing the use of technology as an element in instrumentalizing the cognitive process. The starting point is the reflection: 'I know it happens. What should I do next?' with the intention of providing 'tools' for the individual to establish new ways of transforming and linking to reality.

Coming to environmental education, this new strategy for instrumentalizing knowledge aims at individuals being able to: a) internalize the concept of 'sustainable management', b) establish new relations with the environment, c) define personal actions of environmental management and conservation, and d) identify with and locate themselves within the community in order to become accountable for the environment at the individual and collective levels.

Sustainable basin management does not only depend on expert information and knowledge about the region, it also involves the exercise of traditional and current practices by the populations who live in the basin, who are at risk and need to be preserved. This means that it is not sufficient for experts to have knowledge of problems and solutions, it is indispensable for *agents* – the affected populations and the authorities – to have common exchange codes in order to communicate and make decisions. Some types of knowledge are easily reproduced and distributed to a wide number of users at low cost; however, there are other kinds that cannot be transferred unless intricate links are established, encompassing networks and intensive learning relations, as well as using considerable resources to codify and process information (López/Solís, 2003).

In order for a community to move from their particular perception of a problem towards schemas to solve it, it is necessary to generate *technical information* platforms (knowledge) that enable a community to understand the causes that generate a given problem, and afterwards to define the actions, tools, and methodologies needed to solve it; this is called making a *strategic plan*. The transition from the perception of the problem to the development of a strategic plan is called *appropriation of knowledge.*

Humanity is entering a stage of social, economic and political restructuring derived from the awareness that we are part of a global village; the flows of energy and raw materials at global scale force us to reconsider previous approaches to, perceptions of, and management of the environment. Thus, basin management has come as an alternative to many of the changes that human beings ought to face at this stage of globalization; integrated and efficient natural resource management is a response that calls for sustainability.

Originally, basin management was based on mass production of foods and services in order to keep supplies for an ever-increasing population constant. Later, basin management was geared towards the extreme conservation of natural resources. In the recent past, numeric modelling was the trend, in order to predict potential scenarios based on practices of exploitation. Today, with the awareness that natural resources are rapidly being exhausted at the same time as populations and creature comforts grow, we have to face the administration of remaining resources with the commitment to generate self-sufficient systems in order to guarantee the survival of future populations.

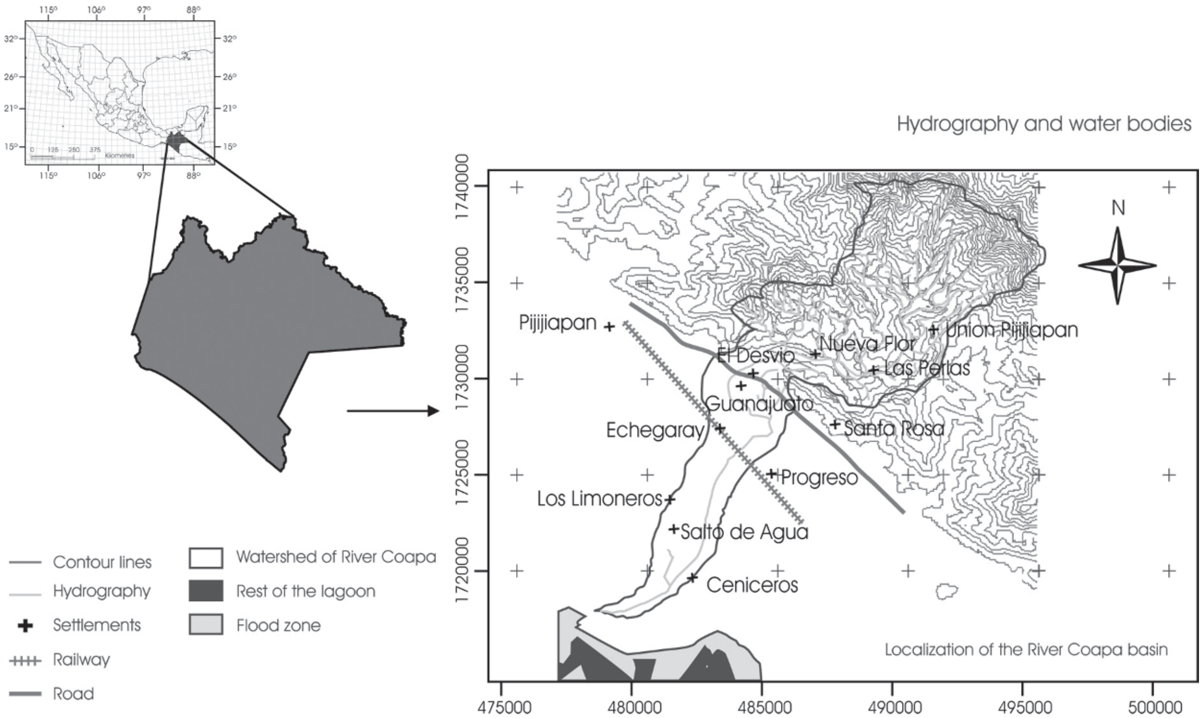
Social intervention as a practice of translation also addresses another element: the socialization of knowledge developed by expert institutions and directed towards consensual decision-making in order to evaluate the impact of public policies over proposed management strategies, its monitoring, and amendments. In its initial stages, this research was applied to rural basins where agricultural production predominated. Productive processes were geared to maintaining and/or recovering natural ecosystems.

26.2 Background

Integrated management geared towards prevention is ever more common. Firstly, because it constitutes a holistic approach that enables identification of the most pressing issues relating to a problem. Secondly, because in the face of disaster situations and in economic terms, preventive actions are cheaper and easier to implement than corrective or even emergency actions. The WHO estimates that presently around 3.5 per cent of children less than one year old and born in communities suffering conditions of extreme poverty die due to easily preventable diseases; this means that these deaths could be avoided with an investment of lower than US $5.00 per individual through preventive actions such as vaccination, sewerage, and nutrition (World Bank, 2001).

This new approach is evident in the programmes of the *Ministry of Government* (SEGOB) with its three sub-ministries: Civil Protection, National Defence, and the Navy. They are in charge of protection plans in cases of flooding, landslides, forest fires, and earthquakes, which constitute the core of the *National Fund for Natural Disasters* (FONDEN). These programmes have two structural components: a pre-

Figure 26.1: Localization of the study area. **Source**: From the authors.



vention stage with preventive actions and dissemination of preventive information, as well as emergency plans such as DN-3 at the Ministry of National Defence. In the realm of civil protection, ministries such as the Ministry of Health, the National Water Commission, and the National Meteorological Service collaborate with the Ministry of Civil Protection in order to prevent impacts on health and weather-related impacts (SARH, 1975). These ministries share the bi-structural programme comprising informative-preventive and emergency-contingency phases (CONAGUA). Currently, Mexico has been catalogued by the WHO and the UN as one of the countries with the highest risk of natural disasters, and thus special resources have been obtained from the World Bank and other funds in order to foster a culture of prevention in areas ranging from hurricanes and earthquakes to epidemiology (World Bank, 2000, 2000a).

The most frequent illnesses that cause the highest damage at the global scale are those that propagate via water polluted by human and animal faecal matter and urine. In these kinds of illnesses, an infection occurs when the pathogen reaches water that is consumed by a person who is not immune. Most of these illnesses – cholera, typhus, dysentery bacilli, hepatitis, etc. – have a classical faecal-oral transmission route, and outbreaks are characterized by simultaneous contagion of different people who use the same water source (Secretaría de Salud, 2005). On average, it is estimated that five million Mexicans have diarrhoeic illnesses that are related to the consumption of poor quality water; among them, children under 5 years of age are particularly affected; this represents the third most common cause of infant death nationwide according to a report by the *Federal Commission for the Protection against Sanitary Risk* (COFEPRIS), Ministry of Health. This report notes that 17 states in the country have deficient clorination of potable water, at less than fifty per cent. This includes also the state of Chiapas (Secretaría de Salud, 2005).

The study area is shown in figure 25.1 in the preceding chapter. The communities in the region suffer from endemic gastrointestinal illnesses as they lack sewerage systems, health clinics, and potable water; they also suffer weather and environmental conditions throughout the year, with fifteen extreme events per annum, including flooding and temperatures higher than 34°C. The lack of services is also caused by the geographical situation of most of these communities, which are irregular settlements with difficult access routes. The way in which settlers face these challenges is by using water for human consumption directly from streams and discharging wastewater into the streams, with livestock also defecating freely, and this is exacerbated by indiscriminate use of agrochemicals for agricultural crops (SAGARPA 1999, 2000, 2003, 2004). All these factors contribute to annual epidemiological outbreaks which are transmitted from one community to another by water streams (Castro/Galván, 2005).

In social terms the communities that populate the basin are considered highly marginal; their economic-productive capacity is extremely low. The setting is not economically viable, with associated social conflicts and a precarious capacity for making decisions about the necessary basic services; these populations are dependent on local and regional political conditions. In the face of such vulnerability, the communities have a very poor perception of local authorities, as municipal authorities make use of federal resources allocated for emergency situations and distribute them according to political preference and proselytism. In addition, if families or communities manifest their political preference openly, they can be banned from receiving federal aid for emergencies in the future, and not benefit from special programmes designed to combat extreme marginalization. This situation changes with each municipal government, which means that all communities have been chastised for their political preference at some point, and this generates resentment towards government actions related to emergencies as well as a strong mistrust of preventive programmes at any level (Castro/Galván, 2005; INEGI 1987, 2004, 2004a).

It is thus that the inhabitants of the River Coapa Basin suffer every year from floods and epidemiological outbreaks (Galván/Gómez/Velez, 2001). As soon as CONAGUA makes a statement regarding the start of the hurricane season, these people flee to special 'corrals' located in the mountain region of the basin. Economic losses associated with these events, including economic and material losses in the household, range from 50 to 80 per cent of family assets, making poverty an annual cycle (Castro/Galván, 2005).

As part of the social intervention strategy, a series of community workshops were designed in the basin, in order to provide settlers with a clear cause-effect image of environmental conditions and their annual risk situation. The ultimate objective has been for each community to generate an emergency management plan for the basin, using adequate technical information, in order to improve their quality of life (Castro/Galván, 2005).

26.3 Objectives

26.3.1 General Objective

The aim of this research is to provide the inhabitants of the basin with a tool with which to face complex problems so that they can split them into apparently isolated and easy-to-handle solutions framed in their own terms and language, so that individuals can instrumentalize knowledge and generate solutions to the best of their abilities.

26.3.2 Particular Objectives

This chapter has three particular goals:

- to translate expert and technical knowledge to local agents (inhabitants and authorities);
- to establish channels for effective communication that enable consensual decision-making; and
- to generate a network of agents directly involved with these problems in order to organize concrete actions to face these challenges.

26.4 Methodology

A first approximation, using reductionist approaches, to facing complex problems is simplification; the strategy is to split complex situations into isolated issues, as apparently simple problems can be solved in a step-by-step manner. However, if it is not possible to split problems, it is hard for isolated solutions to solve overall situations.

As a response to the deficiencies inherent in the atomistic approach, new interdisciplinary models have emerged with a strategy that, instead of looking at problems within single disciplines, seeks to analyse them globally, linking different disciplinary outlooks.

The main obstacle with this approach has been the lack of efficient cross-discipline communication, given the particular methodologies that each discipline normally uses to address problems. However, this approach seeks to find connections that account for overall problems, to detect cause-effect relations – even looking at problems and possible solutions in a fragmentary way – in order to make inferences as to the actual and possible relations between the systems under study.

Given the complex nature of relations in human, physical, and biotic systems, a more suitable systemic approach is used in order to establish cause-effect relations and complement these with statistical elements where these are quantifiable. Specifically, and due to a lack of homogeneity, each system presents a typical characteristic: the human system has unquantifiable problems with high time dynamism; physical systems have easily quantifiable problems that are stable in time; whereas biotic systems have quantifiable and highly time-dynamic problems.

In order to study the relations between the components of a system, the systemic approach suggests that they need to be at a macro scale and often to have a random component –they are known as *second-order*. Internal relations of components (variables) require well-defined and unidirectional phenomena in terms of time and space; they are known as *first-order* relations. They create a multidimensional structure into which a great amount of information is inserted, stemming from different domains and disciplines. Thus, we can conclude that the system is greater than the sum of its parts; it is an indivisible whole that loses its essential qualities when dealt with in separate units.

Relating this to basin analysis, and furthermore establishing an "Integrated Basin Management System", this approach is most appropriate when we are dealing with complex, recursive, and self-contained systems, where an analysis of the internal reference frameworks enables us to return to the initial departure point, or at least not to lose track of it. Establishing cause-effect relations in hierarchical and directional systems with basic elements enables us to evaluate them numerically.

Natural phenomena are complex multidimensional systems, where actions on one variable affect the rest of the system through direct and quantifiable relations (first-order), and through indirect, unquantifiable relations of a higher order. Given this, it is possible to split the basin into simpler sub-systems (not variables) that maintain the original structure of the complex system in order to establish cause-effect relations and store data. Thus, approaching, analysing, and evaluating each sub-system enables us to generate a unique reference framework that can be applied and replicated and is also valid for other components of the system. Information analysis includes adjustment of empirical models and correlation matrices, and generation of quality indicators using geographical information systems.

Nevertheless, all this information must be translated into terms that are familiar to inhabitants in the basin and to decision-makers, so that they can understand, assimilate, and use it. Only in a participative schema can the free transmission of information be guaranteed. In order to attain this, it is important for knowledge to go through the following stages (Peñalva/González, 2005):

- *Academic concept*: refers to available documented information regarding topics, aspects and elements of teaching; accepted definitions are not questioned or revised in order to validate them according to individuals' circumstances, regional characteristics, or environmental demands. For the individual, academic concepts are abstract and rigid entities that are managed though memory.
- *Knowledge acquisition*: this step refers to "knowing something"; it is linked to the academic presentation of concepts, where the object of knowledge is not analysed and consequently its validity and application by individuals is marginal or nonexistent. Thus, it remains foreign.
- *Knowledge comprehension:* at this stage the individual applies one or more methods of analysis to the object of knowledge. Normally this process entails personal discoveries in terms of lack of capacities; these can be either intellectual (lack of conceptual tools) or contextual. This is the longest process as it implies the definition of the object of study, the way to approach it, and the analytical processes to be applied (meaning the definition of technological tools and strategies used in order to analyse the problem).
- *Internalization of knowledge*: as a consequence of the stage just outlined, once the object of study is known and understood, it is assimilated as 'everyday knowledge', and when an individual is questioned about it she or he does not provide an 'academic' definition but rather more comprehensible examples with personal applications. Phrased differently, an individual identifies the concept in its immediate environment and establishes cause-effect relations between the object of study and her- or himself, establishing conclusions such as 'this affects me', 'this is convenient to me'. The process of internalization, unlike the process of knowledge comprehension, is based on individual values and heavily influenced by the psychosocial framework. It is therefore crucial to identify values that can support the strategies of individual internalization (how does this affect me?) and instrumentalization (what can I do?).
- *Knowledge appropriation:* in this last stage, the individual expresses concepts in terms of a personalized cause-effect relationship, i.e., the individual understands the implications of a given action and tries to apply them in specific environments, while

hoping for the benefits they might bring, that is to say, the individual accepts responsibility over her or his actions and over the effects that they have on the environment. Once identified, actions become a part of habits and are conceived and stimulated either positively (they feel 'important', 'better', 'recognized') or negatively – becoming an obstacle for development, saddening or irritating the individual ('I cannot study with this noise'). The culmination of this process is when the individual lacks the technological tools with which to face her or his reality, which leads to impotence and/or indifference as negative values, and then empowerment when the individual attains such tools.
- *Individual instrumentalization:* this step is not part of the cognitive process, given the current trends of the technological development; the absence of technological tools puts an individual at a disadvantage. This step refers to providing general, technological, and methodological tools for an individual in order to allow her or him to relate to the object of study in a different way, in order to face old problems with new habits and tools that reinforce positive values, facilitate the attainment of objectives, and guarantee long-term subsistence.

26.4.1 The Role of the Translator

In summary, the role of the translator is to highlight academic concepts such as 'ecology is the science that studies the environment', and interrelated concepts such as 'ecology is the science that studies the environment and I am part of the environment. Thus, if the environment is damaged, I lose my quality of life. I have to look after the environment. I will do it using the following strategy(ies)…'. These new types of knowledge generation permeate disciplines and life domains where knowledge is generated from a social perspective and is distributed in a space where agents with different social natures converge: organizations traditionally devoted to knowledge are now seen as facilitators or translators in the construction of a new knowledge-learning schema.

The function of translation is a facet of the construction of agents and of specific action modes; there is no doubt that the academic involved in linking knowledge has or may have personal interests other than those of the three core agents.

Universities build bridges of knowledge and understanding. They operate as organizational translators that are able to help social agents find their own answers and generate social innovation, enabling communities to modify their perception of problems and to identify technologies and strategic solutions for them. This new role of educational institutions is still in a construction phase, as educational institutions need to revise and redefine their vocation, and communities must assimilate new ways of linking with other types of institutions.

Even if these interests are not manifest, they exist as potential forms. Thus, the academic is always considered as a latent linking agent. Academic interests will always go beyond the rationality of profits or of market logic as they are also nurtured by the goals of knowledge generation or problem solving with a social impact. An academic always has a rationality distinct from an enterprise because she or he derives prestige from cutting-edge research and not from pursuing strictly commercial interests.

For a university, the core aim has been achieving resources to pay for research. It is only afterwards that new secondary agendas have emerged, such as the retention of important academic figures who may leave academia in order to go to work for a higher income with private enterprises.

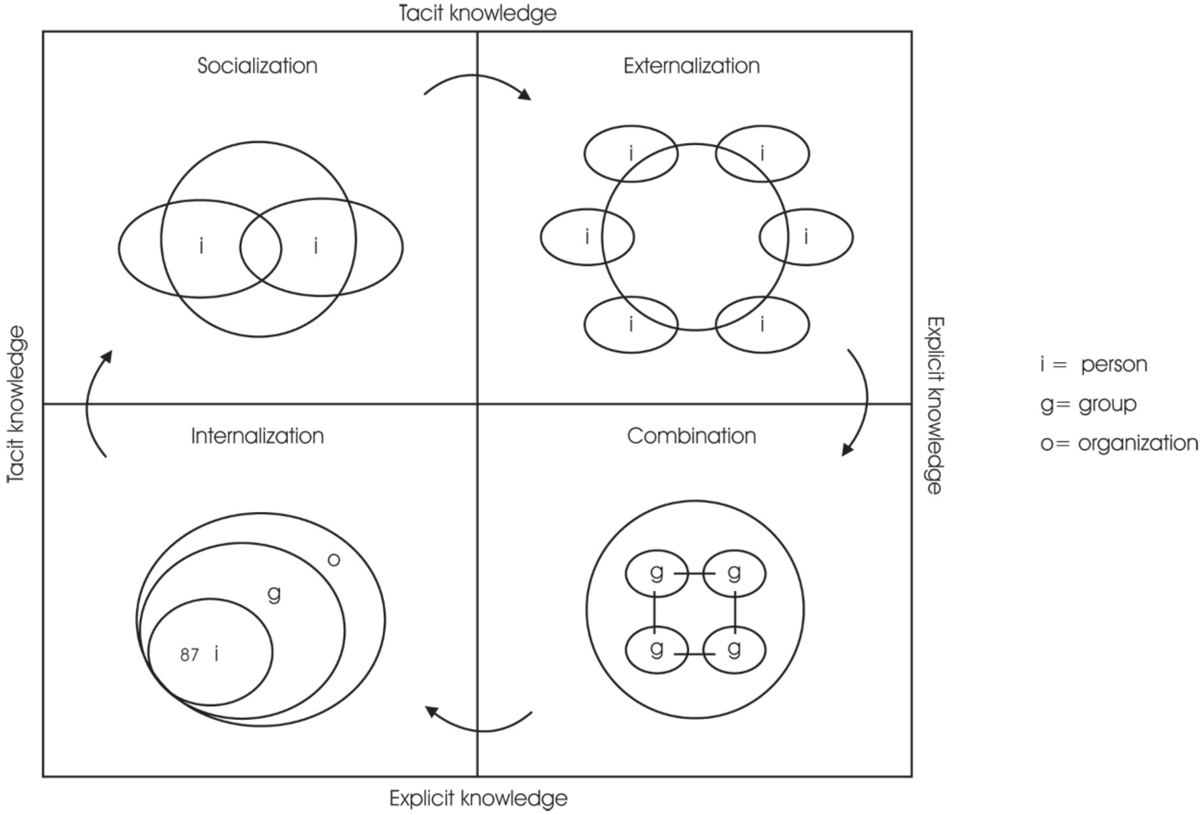
To know 'who' is not only to know 'how', it is important to identify reliable capacities and experts, as well as to know how to 'translate'. This is a complementary competence that will become increasingly important in a knowledge web. Innovative webs normally stem from relations between a 'core innovator' and 'distant sociometric' webs. Thus, the role of the translator is fundamental.

Some individuals identified as translators are university researchers with a career in business, technocrats with work experience in universities, and students with high mobility who have learnt to work in different organizational environments. Besides this, the salient characteristic is that even if translators are not always dominant within the knowledge web, they are nevertheless essential; this applies even to students attending classes, students drafting theses, and students doing social service.

26.4.2 Characteristics of Translators

Individuals linked by a bridge tend to occupy marginal positions in their primary webs. What is most important is not the strength or weakness of the bond, but that some bonds are the only link there is between webs that would otherwise be totally disconnected (Luna, 2003).

Figure 26.2: Cycle of knowledge management. **Source**: Solis and López, 2000.



Another important point in the role of the academic translator is pretending that there can be neutrality and distance from the object of study. We think this is impossible, because the academic translator is modifying the object of study from the moment that the translator interacts with it; this is the role of the academic translator in the construction of the problem of the group, organization, or society.

26.4.3 Construction of the Problem

From the standpoint of the social construction of reality, a problem does not exist if it is not framed in terms of the people that face it, i.e., a problem emerges and is constructed based on its interaction with individuals; this is called *cognitive interactivity* (Savall/Zardet, 1995, 1996, 2004). This is the basis of *empowerment* given that the solution to a problem can be outlined by agents who are not involved with it on an everyday basis; that is, one of the bases for promoting preventive actions is providing agents with support in order for them to be empowered and to become decision-makers.

There are three fundamental problems derived from the *link* between academia, society and government:

1. recognizing the need to cooperate in order to solve problems; reframing the social role of an organization, whether it is an enterprise or a university;
2. the problem posed by the existence of *structural holes* (organizational holes) in apparently distant organizational worlds; and
3. the problem of lack of shared common codes generates a communication problem linked to semantic noise (González, 2006).

Translation has different functions: it operates at the level of cognitive orientation, in inter-organizational relations, in disciplinary integration, in codification and decodification of knowledge, and finally at the level of interests and negotiations (Luna, 2003). The phase of construction of a common language is fundamental, where the academic platform translates knowledge to the community and the government, generating common codes through workshops. This is essential, as it presupposes a kind of pact and the possible development of an information web.

26.5 Results

As a technical information platform, the point of departure was water quality linked to outbreaks of hepatitis, cholera, and general diarrhoeic illnesses, their occurrence in spatial and temporal terms, and establishing the times and places of their occurrence as well as potential preventive actions.

Regarding floods, the point of departure was the rainfall linked to floods and landslides, as well as water puddles and pools; rain distribution, water and land run-off were all considered.

In terms of environmental education, this new strategy for instrumentalizing knowledge seeks for individuals to: a) internalize the concept of 'sustainable management', b) establish new particular relations with the environment, c) define personal aspirations in terms of environmental management and conservation, and d) be identified within the community in order to have specific responsibilities in individual and collective terms.

The workshops used present different forms of knowledge that can be understood as ways in which to anchor social knowledge in the community. This work implies identifying the basic biophysical conditions of the environment, in which the producer must undertake productive activities, and anchoring this knowledge at the social level in order for the community, the authorities, and NGOs to take joint decisions regarding funding and investments that will foster economic development of systems.

The Coapa River Basin is a risk zone located on the Pacific coast, subject to important weather events throughout the year that lead to problems such as floods and excessive erosion which impact on the economies of the local population (Contreras, 1993). Besides this, given that local populations have no other development space, they invade the most dangerous areas of the basin, impacting on its ecological balance and causing the economy to deteriorate further. Erosion is the most obvious physical phenomenon in this system. It is imperative to control erosion and to increase the productive conditions of local subsistence peasants (Arellano, 1994).

Community workshops were undertaken in order to make inhabitants in the communities of the Coapa River Basin aware of the risks to which they are exposed given:

a) the incidence of torrential rain and hurricanes (15 per year on average), causing floods in 4 out of 7 communities settled in the basin;
b) epidemiological outbreaks, derived from domestic and agricultural water discharges to the river and streams, affecting all communities in the basin.

Information used for the workshops stems from a series of investigations undertaken by the Metropolitan Autonomous University, the Institute of Ecology, and the Ministry of Health. Information generated was systematized in technical research reports that were delivered to different authorities, which together make up the technical information platform that enables decision-making concerning emergencies caused by floods and water-related epidemiological outbreaks.

Workshops mixed agents from the community and government, as well as from the civil service sector, to guarantee the integration of all actors involved in an emergency. The government sector represents resource provision and the organization of the third level, organizations represent structured society and local work groups, and families are the ones to face emergencies and towards whom preventive actions and impact mitigation strategies are oriented.

RAKKSS methodology or the *Rapid Assessment Methodology for Systems of Agricultural Recognition* (Evaluación Rápida de los Sistemas de Reconocimiento Agrícola) is used for the construction of the problem, when the first rapprochement with the community is undertaken, drawing from local concepts that establish cause-effect relations as:

a) changes in the environment and effects of productive activities;
b) normal hydrological processes in the region and their effects on the basin;
c) wastewater discharges and illnesses; and
d) wastewater discharges and temperature processes that facilitate epidemiological outbreaks (Apha/Awwa/Wpcf, 1992).

RAKKSS emerged as a quick and participative diagnostic method for small agriculturalists in Colombia (Engel/Salomon, 1997). Some of the main elements of this methodology are the central role it assigns to agents, objectives, and their mutual links (Solís/Galván/López, 2006, 2007). RAKKSS does not offer a recipe for change; instead it consists of the description of a process oriented towards action. RAKKSS has three stages:

- identifying the problem;
- limitations and opportunities; and
- action plans.

Table 26.1: Management plan generated by the community. **Source:** Authors' research data.

Activity/Level of Action	Vigilance	Prevention	Action
Basin	Community rotation of river surveillance	Communication with other communities and local authorities (basin alert system)	Evacuation plan for vulnerable populations
Community	River and rain surveillance (monitoring) in order to generate early alert systems in the face of landslides and floods	Communication between community members (community alert system)	Identifying a shelter area in every community, making an emergency aid collection and distribution point
Family	Beware of radio communications and alerts Call the municipal presidency every 4 hours when it rains	Prepare important documents inside a plastic bag together with basic security equipment Clear instructions in the face of emergencies	Group evacuation Priority attention to children, pregnant women and aged citizens

The RAKKSS diagnostic methodology was used to diagnose the problem and from there onwards to begin the process of empowerment. Once the physical, biological, and weather conditions that 'cause' the problems are known, the individual feels in control of the situation, as solution strategies can then be devised.

The second stage of the workshop examined the interrelationship between the state and society concerning the environment and its dynamic of risk in human settlements and communities in the Coapa River Basin. Dynamic processes were undertaken involving local inhabitants and authorities in order to establish shared common language codes surrounding the concepts and information addressed by university academics. These codes enable the free transit of information and the definition of common objectives. This activity helps the communities develop the relational and social capital for solving conflicts. The first outcome of this activity is the construction of a web of information for decision-making involving local authorities, community leaders, and local inhabitants.

In the final stage of the workshop, changes in everyday practices were suggested through training (learning by doing) in order to overcome some of the most pressing problems. The communities under study are vulnerable to gastrointestinal illnesses with the following characteristics (Castro/Galván, 2005):

a.) lack of piped water and unhealthy water conditions arising from the inhabitants' use and storage habits (NOM-127-SSA1-1994); and
b.) absence of sewerage in households increases the risk of infectious diseases (NOM-001-SEMARNAT-1996).

With this information, we asked the communities to rebuild their problem locally, and to link it with environmental and agricultural practices. Afterwards, we asked them to link this with the rest of the communities in the basin. Once the problem, its components, and areas of influence were interlinked, the need to establish everyday practices was addressed, as were decision-making processes accountable for each action.

The goal of the first objective was reached, namely that communities understood that outbreaks of diarrhoeic illnesses depend on the existence of agents that cause and transmit disease, on weather conditions that facilitate its propagation, as well as on the presence of vulnerable individuals. The second objective was identifying weather conditions that facilitate propagation and other propagation mechanisms (open-air defecation, lack of sewerage, sick livestock), as well as conditions of vulnerability in the population, in order to suggest prevention and management programmes.

The management plan generated by the community following the three workshops is shown in table 26.1.

26.6 Concluding Remarks

Epidemiological outbreaks directly depend on temperature increases and the presence of water as a means of incubation. Thus, and following the discussion presented above, the conclusion was reached that the critical temperature and rainfall for the emergence of dengue and gastrointestinal diseases is 23ºC and 6 mm/day, a common and active situation in the period from May to October. Knowing this, it is possible to design and implement annual prevention and management plans that can operate from November until April, with a 6 months cover, guaranteeing high effectiveness. Besides this, once preventive strategies have been undertaken, emergency actions and health cover should decrease, so avoiding crises during the high-risk season.

The recommendation for the period September to May is to undertake water management activities such as maintenance of hydraulic infrastructure, sanitation in water sources, raising awareness, and training local inhabitants in clean water management, bearing in mind that the period of alert commences once rainfall surpasses 6 mm/day and temperature reaches at least 23ºC.

The case of Pijijiapan is more complex (IDSM, 1998). Besides the strategies mentioned above, there is a need to address issues related to livestock management, organization of corrals, sanitation, and community wastewater discharges, from the perspective of social participation.

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27 The Governance Crisis in Urban Water Management in Mexico

David Barkin

27.1 Introduction

In Mexico, political, social and technical analyses clearly show that the bureaucracies charged with the public management of the water sector have not only proved deficient in achieving their assigned goals but, even worse, have heightened the contradictions in society as a result of incorrect technical diagnoses, poorly informed processes for designing and constructing infrastructure and allocating water resources, and corrupt mechanisms for implementing policy. The chapter examines more than a half-century of the activities of the water bureaucracy, from the creation of the Ministry of Water Resources up to the present time with the emergence of the National Water Commission, to show that Mexico's highly-regarded technical capacity for engineering in the water sector has left a heritage of environmental destruction and administrative incompetence and corruption that has imposed an unacceptable cost on the nation, a nation that should be well-placed to face the multiple challenges of operating a national ecosystem programme to promote social welfare, economic development, and sustainable environmental management in an era when socio-economic crisis and climate change threaten the country's very foundations. The analysis ends by pointing up the role in today's society of organizations drawn from civil society.

Urban water management has become an important part of the social agenda in Latin America. The significant administrative and political innovations introduced in Brazil placed important parts of the system in the hands of local organizations that operate water agencies which have incorporated mechanisms for citizen participation; in Venezuela, a new pattern of regional water boards has instituted consultation processes to supervise and raise quality of service; in Cochabamba, Bolivia, it became necessary to cancel a private management concession following an avalanche of complaints about abuses and violations of the service contract; after the outbreak of an economic crisis in Argentina, and a conflict between the French firm that controlled water services in Buenos Aires, the national union of employees of the water services companies created a training programme and began to assume management responsibilities in numerous local systems, with good results. There remain a number of examples where the privatization of services has not been questioned: the combined contract in Havana and Varadero, Cuba and several municipal contracts in Colombia may be noted; the privatization of all services in Chile is still a subject of controversy on account of its social and environmental impacts, especially in NGO circles outside the country, although it receives high marks from the global water services industry and international financial institutions (Balanyá, 2007; Balanyá/ Brennan/Hoedeman et al., 2005; ASSEMAE, 2006).

In Mexico, the problem remains an issue of widespread concern. In spite of the long history of institutional reforms, the country still cannot assure adequate urban water service to its population and, if that were not enough, its aquifers and ecosystems continue to deteriorate.[1] Although decentralization is a stated objective of efforts towards administrative reform, the National Water Commission[2] (CONAGUA for *Comisión Nacional del Agua*) continues to be an all-powerful semi-autonomous agency charged with collecting fees and supervising the local water agencies throughout the country. The local administrations that actually operate the urban water systems are under constant pressure to modify their management structures in order to meet international service stand-

1 A large body of laws and regulations make up the legal framework for water management in Mexico. Article 27 of the Mexican Constitution establishes that all water is public property under control of the central government. The National Water Law, amended in 2004, is the basic operative instrument; state laws have created the legal basis for the operation of local agencies as a result of an amendment to the Constitution in 1983. For more details see Ortiz Rendón (1998).

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ards in hydraulic, sanitary, economic, and social terms. However, the federal authorities consider that these standards can only be met with the extensive participation of the private sector. As a result, numerous programmes are being implemented to encourage modernization of the infrastructure and administrative structures, with special incentives included to facilitate private sector participation.

In the sphere of urban water management, the CONAGUA's principal responsibility is to ensure the correct operation of the local agencies charged with water supply for the population and for productive activities in their jurisdictions. This includes not only planning, construction, and operation of infrastructure for water extraction, transport, and delivery, but also the negotiation of inter-basic transfers to supply burgeoning social and productive demands.

The management of watersheds has also been delegated. In this case, local management, in the hands of the local River Basin Councils, has been considered to be among the most innovative structures in Latin America. It places decision-making responsibility directly in the hands of the users, who must supervise water allocation and the operation of the irrigation systems as well as the financing of these functions (Dourojeanni et al., 2002).[3]

To understand the reasons behind these contradictions, as well as persistent inertia in the allocation of subsidies and inequities and inefficiencies in the services, it is essential to not lose sight of the legal structure and the institutions that have evolved for water management in Mexico. Another factor that should be considered is the change in the country's political structure since 2000, when the *Partido de la Revolución Institucional* (PRI) lost control of the presidency after 70 years of rule to the *Partido de Acción Nacional* (PAN), a party with a neo-liberal platform, which enacted its own National Water Plan, 2001–2006, declaring water to be an issue of national security and the need for river basin management to include provisions for citizen participation (Constantino Toto, 2006). An analysis of the subject clearly reveals that these directives have been forgotten in practice.

The legal framework for water resources management in Mexico is complex.[4] Although the framework defines water resources as a property of the nation, it favours private concessions and the transfer of water rights in an unregulated and unrecognized market. Beyond the matter of the environmental protection and social participation (often disregarded), its operation is guided by a growing demand for privatization of access to water. The impact of this model must be evaluated through the lens of modern approaches to an integral management of water resources (taking into account social, environmental, political, cultural, and recreational, as well as economic, demands). In this light, we propose the use of the *'New Culture of Water'* (NCW) framework that emerged from social movements in Spain (Arrojo, 2006; Barkin, 2006).

27.2 The New Culture of Water[5]

Our analysis of the large and complex system of water management on which Mexico depends for its survival grew out of the contributions made by the Spanish social movement *For a New Culture of Water* (NCW). The NCW concept offers a sharp contrast to the dominant focus of water management that assumes that all demands can be satisfied by public works to increase the supply. This construction-based approach reflects a vision of water use that ignores social and environmental impacts, enriching those polit-

2 The CONAGUA was created in 1989 as a specialized agency to centralize all aspects of water management in Mexico. Its broad mandate allows it to deal not only with problems related to the management of the nation's water resources and the state of its aquifers but also to allocate water among users, both public and private, and to ensure the correct operation of the local water agencies and the regional watershed basin commissions, charged with overseeing the local operation of irrigation systems. Ultimately, it is directly responsible for negotiating all the contracts and institutional arrangements that have led the country to the critical situation in which it currently finds itself.

3 Not surprisingly, these councils were conceived as bodies controlled by the most powerful interests in their regions, without any system for consultation or participation with the peasant producers and other significant social groups, including many who undertake water conservation efforts that are crucial for the maintenance and recharge of the aquifers on which the urban and industrial users depend. The devolution of power to these councils has been accompanied by the participation of the private sector in some aspects of service provisioning and production.

4 For an introduction to this body of laws see Ortiz Rendón (1998).

5 An excellent introduction to this subject can be found in Jiménez and Martínez (2003). For further details, see the various chapters in Barkin (2006), especially Arrojo (chap. 2), who won the Goldman Prize for environmental activism in 2003. Also see Barkin and Klooster (2006), Esch et al. (2006) and Arrojo (2006).

ical groups aligned with the economic (agricultural, industrial and financial) elite at the expense of large segments of the population. The alternative proposed by the NCW is based on a model of integrated sustainable development that examines policies in terms of the social appropriation of water and takes into account its limited availability and its environmental importance as well as its effect on social and inter-generational equity.

The NCW offers a framework for establishing criteria for the social appropriation of water in which administrators play an important but not an all-powerful role. However, the NCW does not fully encompass considerations of the role of the public sector in the regulation of water management and of urban public agencies. In spite of its emphasis on demand management and its concern with watershed management, it does not consider the way in which the public sector will ensure that each component part will contribute to the larger goals.

The NCW has not defined a position with regard to privatization, except in so far as it insists that strategic decisions on financing should include citizen participation. Without doubt, the market generates incentives that lead to a greater efficacy in water distribution and productive water use, be it in agriculture, industry, or urban households. However, it has been widely documented that market dynamics are blind and ineffective when dealing with environmental or ethical matters or when considering problems of equity. For this reason, accepting the market as a 'magic wand' that can guarantee an advance towards a 'New Culture of Water' would be a grave error. Consequently, privatization and the administrative mechanisms for regulating water systems – be they private or public – are subjects that require careful study and public debate.

NCW uses the term *culture* to highlight the need for a paradigm shift. In this regard, water is not simply a factor of production but rather has great value in all aspects of social life and the environment. It is an integral part of dynamic cultural landscapes and a critical component of ecosystems. Putting this framework into operation requires changes not only in governance and politics but also in society as a whole. In Mexico, there is a marked dependence on underground sources of water and an incapacity among social movements to overcome the decided opposition of authorities (reinforced by the excessive use of police powers) to permit citizens to participate in their management. The starting point for a proposal based on NCW is the need to introduce radical changes based on the principles of equity, solidarity, ecological, social and economic sustainability, and participative democracy. To achieve this package of goals, the framework proposes four fundamental priorities as guides for policy formulation:

- water as a human right;
- water for environmental needs;
- water for social and community needs; and
- water for economic development.

NCW also points to the need to severely punish illegitimate uses of water. It is not only a matter of applying administrative fines as is mandated in Mexican law, but rather to implement measures to end these practices, which amount to as much as 70 per cent of the total activity, including practices such as excessive withdrawals of groundwater and contaminated discharges to surface water bodies, to mention but two of the most significant.

The Mexican context is different from that in Spain. There is a greater dependence on subterranean sources and a very weak social organization that might promote a new culture of water. The point of departure for the NCW is the need to introduce radical changes that would favour a *New Culture of Water*, based on the principles mentioned above.[6]

27.3 Diagnosis of Urban Water Management in Mexico

The 1983 constitutional reform established the duty of local governments to assume responsibility for water management and treatment (see note 4 above; Olivares/Sandoval, 2009: 49–56). Most of these agencies are small and improvised, staffed by people with little administrative experience and even less technical skill. Their directors distribute political favours and take advantage of their posts to climb the political hierarchy. Of the almost 2,500 counties in Mexico, fewer than 450 have semi-autonomous entities that can operate independently of the governments of which they are a part; these agencies are members of the *National Association of Water and Sewage Enterprises* (ANEAS). Less than a dozen have private participation or joint enterprises, or are concessions that have won a public bidding process to manage all or part of a system. In Mexico, several of the giants of the water

6 A proposal in this regard for its implementation in Mexico in the metropolitan area of San Luis Potosí can be found in Tagle and Barkin (2008).

sector on the international scene – Suez (Ondeo), Aguas de Barcelona, Vivendi (Veolia) – as well as other international firms of lesser importance along with some national ones participate in the management of one or more local water and sewage systems. Recent innovations have established the separate concession of sewage systems as independent businesses, frequently under the scheme known as BOT (*build, operate and transfer*), in which the costs are transferred to the users or to the local governments (CONAGUA, 2003). At present, less than one-quarter of the systems have sewage treatment plants and fewer than 22 per cent of these are currently operative.[7]

Local government in Mexico is confronting an almost insurmountable challenge: ensuring drinking water supplies and sewage services in an efficient and economically viable manner, while at the same time being socially and ecologically responsible. Most local agencies lack the financial means to construct and/or modernize their infrastructure as well as trained personnel to update their administrative and technical systems; they cannot hope to fulfil their obligations to meet the hydraulic, sanitary, economic, or social standards that define adequate service. As a result, the CONAGUA has become a powerful operator, responsible not only for supervision and regulation but also charged with the modernization process itself; as part of this process, it has imposed an iron-clad control on the system, intensifying its efforts to promote the international private sector for the modernization and management of the infrastructure.

At present, the water systems are not self-financing, even if they have the agreement of their clients to pay water fees, something which is very rare. Most of the agencies are plagued by enormous problems; among them water leaks in the distribution networks, which are poorly designed, obsolete, and older than their useful lives; they have been built with inadequate materials, maintained by poorly trained people, and suffer from decades of neglect.[8] Aggravating the situation is the absence of processes to manage the ecosystems that provide the water and receive the sewage discharges. The untreated 'black waters', as they are called, are frequently used to irrigate fruits and vegetables, with the product going directly to local markets (Lemus, 1995; Downs et al., 1999).

Complicating the water management problem is the inability of the Mexican authorities to ensure the proper enforcement of the laws, national standards, and payment for access to this treasured resource, especially among the larger users; there is widespread abuse of the permits for operating wells and a worrisome lack of control of contamination as well as a lack of a culture of 'paying' for water services.[9] These problems are exacerbated by many unresolved technical and political matters in the Mexican system: water is the property of the nation, according to the Constitution, but has been manipulated as if it were appropriable for private and political gain. The governmental structure and pattern of operation sanctions controls the situation through regional power groups and allows water use without oversight or accountability. A profitable parallel market has emerged to transfer water rights to commercial and industrial users; these groups compete with the local agencies, exploiting the same aquifers at the expense of ecosystems and social welfare. As if this were not enough, the operators (agencies) themselves face problems of illegal connections; often these are installed for medium and large sized enterprises that wield a great deal of power on the local scene.

Urban water service continues to be anarchic. Much consumption is not measured and many users are not even registered. Finally, scant attention is directed to the problems of the 'new culture of water', a model that would require a discussion of how to allocate water among different sectors and how to ensure its rational and frugal use. There are no socially equitable strategies, since both administrators and users lack information and education to modernize and transform present practices.

In contrast, many industrial users are installing their own treatment and recycling infrastructure because the CONAGUA has implemented a system of fines for the discharge of contaminated waters. In spite of its considerable efforts, the CONAGUA estimates that the national urban system as a whole has an efficiency coefficient of less than 30 per cent, based on losses of more than half in distribution and an index of less than 60 per cent for the water fees that are really invoiced.

It is probable that the most important effect of the regulatory reform in the Mexican water sector

7 For a detailed analysis of sewage treatment in Mexico see the two chapters by Jiménez Cisneros and Pacheco Vega/Vega, in Olivares and Sandoval (2009).

8 There are notable exceptions to these generalizations that are discussed below.

9 An informed observer and executive of a leading international firm characterized this problem as a "lack of a culture of billing" as a response to political and social pressures.

started in 1992, when the emphasis was placed on the privatization of urban water services and hydraulic infrastructure for the future. In 2010, in Mexico and in a large part of the world, private companies control less than 5 per cent of consumption, but following the leadership of the World Bank and industrial bodies such as the World Water Council, the government argues that the public sector lacks the administrative, technical, and financial capacities to confront the challenges of assuring adequate supplies of high-quality drinking water, sewage treatment, and drainage infrastructure in the coming period (CONAGUA, 2003).

This analysis of the urban water supply starts from the broadly accepted premise that the system is very badly managed and presents serious problems due to the lack of precise information, uncertainty about the state of the aquifers, and the absence of technical and administrative capabilities to define and implement basic management functions; most alarming of all is the lack of definition of the scope of the Mexican water sector.

This chapter examines some of the general problems and specific details of urban water management in Mexico. It is clear that the country finds itself at a crossroads: its ecosystems and especially its watersheds are threatened, the aquifers are shrinking, and the water is being polluted. A diagnosis of the international water companies that operate in Mexico, as well as the social, economic, and environmental impacts, all contribute to understanding and providing an impetus for confronting challenges faced by national institutions, political classes, and most importantly the citizenry, in trying to resolve the problems of water management.

27.4 The Regulatory Framework

There is an international consensus that public services should respond to social needs, respect the environment, and meet well-defined technical and administrative standards. This task requires an impartial administration for regulation, with authority and mastery of the subject, to ensure that the agencies comply with contractual obligations so that service quality is assured for all users and the ecosystems on which they depend are protected.

Perhaps the greatest obstacle to the improvement of public services in Mexico is the absence of an effective system of regulation or of mechanisms to demand accountability. The country lacks an independent capability of exercising oversight to determine progress in meeting environmental, administrative, technical, and financial standards. The local agencies have no effective means of upgrading their capabilities and no process is in place to evaluate their performance; there are no mechanisms to ensure improvement in public or private bodies, in spite of the many programmes operated by the government; even the state commissions and the auditors are incapable of certifying the actual state of these operations. A constant complaint of the central government is that local public agencies lack basic capabilities; these challenges apply almost equally to the private sector, because of structural and institutional barriers.

From the perspective of the international community, the local scene appears strangely incoherent: nationally, the CONAGUA is responsible for administering a system in which the local agencies are, more than ever, dependent on federal funds for investment and even for their operation; they must follow structural guidelines, but without help to improve their abilities to identify and resolve local problems. Formally, the CONAGUA limits itself to collecting information about the principal operational indicators of the local operators; but most of these groups do not have a formal information system or an analytical procedure that permits them to provide the required information.

There is no oversight by federal and state government authorities of the local water agencies, and the users do not have recourse to any formal appeal mechanisms in the case of unusual increases in tariffs for their water or lack of it. Additionally, most users have become resigned to the fact that their water is not fit for human consumption, that it is not always available, and that the pressure in the mains is often insufficient to fill their roof-top tanks. These local agencies should subject themselves to regular accounting by the municipal government, and they avoid efforts by the federal government to audit their accounts. Perhaps the only exception to this pattern of irresponsibility is the case of programmes financed by federal funds, international funds, or development agencies.

27.5 Private Participation in Water Distribution in Mexico[10]

The privatization of water services in Mexico continues to be marginal. There are only four metropolitan areas in which the principal international agencies participate. It is surprising that some systems are operated by private companies without effective supervision. In what follows, we present a review of these experiences.

27.5.1 The Case of Aguascalientes

Aguascalientes, an industrial centre in the semi-arid centre of Mexico, was the first system to be privatized in 1993, during the height of the neo-liberal reorganization of public policy that was being implemented in the central government. The foreign parent of the new local operating company is a subsidiary of the French giant, Veolia. Ironically, the institutional change was counter to the entrepreneurial interests of the political right (PAN) in the state, as contrasted with the effective campaign being waged by the ruling party at the time (PRI). Although the state authorities had the authority to regulate tariffs and establish operational rules, the new concessionaire was able to set its own rules and reduce its financial burden by transferring to state and municipal governments all responsibilities for building infrastructure and offering service to the 'marginal' communities. There are numerous and continuing complaints about the poor quality of the water service as well as a growing awareness of the deterioration of the watershed in which the city is located; many of the sub-basins have been desiccated, causing parts of the city to sink, with large cracks in the surface and enormous social and geological risks as well as extensive damage to many homes, especially in the poorer sectors of the city.

The tariffs are among the highest in Mexico and the aquifer on which the city depends is being dangerously over-exploited whilst no measures are being implemented to reduce consumption or change the management strategy for the watershed. The local regulatory institutions have proved unconcerned by this damage or lack of control of demand; they are being held 'hostage' by the private water management company. Although not accepted by the authorities, many experts forecast that if the situation continues as at present, the region will be one of the first to suffer a regional crisis due to lack of water, obliging the region to dramatically reduce its plans for economic expansion.

27.5.2 The Case of Cancun

In 1993, a private consortium won a twenty-year concession to manage water services in Cancun; this group was headed by the Mexican construction company GMD, together with a Mexican partner (Grupo Bal, a holding company that includes the mining firm Peñoles and others in the insurance and retail commerce sectors), and the water services subsidiary (Azurix) of the aggressive US giant Enron. When the foreign partner was forced to sell its shares because of its financial problems at home in 2001, it negotiated a deal with another giant in the industry, Suez des Eaux (Ondeo), which was able to obtain financing at privileged rates from the Mexican public works bank (Banco Nacional de Obras y Servicios Públicos) to buy the local company (Aguakan) and extend the concession for an additional ten years. The state agency charged with the oversight of this operation has been trying to learn how to regulate this operation, but its own internal problems are complicated by frequent changes in leadership and the complexities of operating drinking water and sewage treatment systems on the rest of the Riviera Maya, an area of rapid growth with many 'irregular' housing and hotel developments; the state agency continues to wrestle with understanding the intricacies of the administrative practices and accounting systems used by the French administration and is handicapped by a lack of adequate legal authority that would allow it to forcefully exercise its fiduciary responsibilities for overseeing these operations. The hotel industry (about 65 per cent of the invoiced water) complains about the high water rates fixed by the state agency and a number of units have installed their own desalinization plants to control costs; in contrast, individual consumers are the beneficiaries of this approach, with low tariffs as a result of the cross-subsidies decreed for their service. Local observers point to the lack of formal service in the 'marginal' areas on the fringes of the city, where people are supplied from tankers to supply their needs.[11]

27.5.3 The Case of Saltillo

A joint public-private venture manages water service in Saltillo, an industrial city in the northern desert. Created in 2001, it is operated by the Spanish Aguas de

10 These experiences are examined in greater detail in the various chapters in Barkin (2006).

Barcelona through a Mexican subsidiary, InterAgBar. Although the board of directors is controlled by local businessmen, it is plagued by an inability to exercise its functions effectively because of its inability to conduct investigations of the operations, its lack of technical expertise, and the lack of veracity in the information it receives; a particularly notable example of these problems is the evaluative study the board commissioned by consultants from the highly respected Instituto Tecnológico de Estudios Superiores de Monterrey that was considered unacceptable by all the groups involved. Of all the privatization experiences in Mexico, this is by far the most highly criticized, in part because a local watchdog group has among its members an experienced hydraulic engineer whose independent evaluations continually question the company's claims; during the first two years of operation of the concession, water tariffs increased from 32 to 68 per cent, in contravention of the legal limits that imposed increases tied to the rate of inflation, which was about 11 per cent. An investigation of this accusation by the state congress confirmed these and other irregularities in financial dealings, including unauthorized charges for changes in service, irregular mechanisms for purchases and contracting services, and an intensification of labour conflicts as a result of harsh management practices. In spite of these problems, the company is considered a success by the business community because of improvements in service quality and the increase in its service area. However, its flagrant violations of the terms of the concession continue to provoke highly visible protests by users.

27.5.4 The Case of Mexico City

The most important private sector experience is that of the four private contracts for water management in Mexico City. In 1994, the city was divided into quadrants to initiate a bidding process for improving water services; the winners were to create a complete roll of clients in each zone, install meters, and improve collection practices as well as provide maintenance services for the 'secondary' distribution network that delivered water to the users. Ten-year concessions were let to Mexican companies that were created with major international partners with experience in the industry. During the following decade the companies were reorganized, and one of the foreign partners sold its shares to another of its competitors after realizing the complexity of its commitment. In spite of the dramatic political changes in Mexico City, when the left-wing *Party of the Democratic Revolution* (PRD) won the first local government election, the population has still not realized that the administrative apparatus of the water system with which they are in direct contact is in private hands; the renewal of these concessions was handled very discreetly in 2003-2004. The terms of the contracts as well the supervision of the operation is established by the City's semi-autonomous water agency, which exerts very little effort to try and force the companies to comply with their commitments; tariffs and connection costs are fixed by the local legislature. Although technical efficiency and income has increased, a substantial segment of the population still does not pay its water bills, including many of the largest consumers, and many of the federal government agencies in the City. The concessions have contributed to creating a more reliable computerized database of users, and meter readings have enabled an analysis of water use and improved billing practices and a new ability to identify leaks electronically. But large segments of the population still lack adequate service, both in terms of quantity and quality, and the infrastructure continues to prove inadequate to meet the demands of a system that is poorly designed to meet the challenges of an area where water management practices lead to the irregular subsidence of the land and rainfall creates intolerable situations as sewage floods into homes much too frequently.

27.6 Public Participation in Urban Water Service in Mexico

Water services in most of Mexico's largest cities are provided by decentralized public agencies. These para-municipal organizations are a very heterogeneous group that fulfil their functions with widely varying degrees of success. To review this range of outcomes, information about three outstanding examples of public companies, mentioned in Barkin (2006), will be briefly summarized. The title of best public water system is generally given to the agency in Monterrey, the second largest city in Mexico. Others that receive

11 In its defence, the company commented that it cannot invoice water services to land lots without a valid land title, even though homes have been constructed there; historically, water bills have been accepted as proof of residence and ownership, and the local authorities are unwilling to provide these communities with documents that would legalize ownership, since many were established as a result of land invasions. A similar problem exists in practically all urban areas of Mexico.

high marks include two cities on the northern border with the US: Tijuana, a centre of the maquiladora (export assembly) industry, and Ciudad Acuña, an intermediate-sized city. León, Guanajuato, a leather tanning and shoe manufacturing centre, was the first large municipal water system to be organized as a decentralized agency in the 1980s, during the initial period of enthusiasm for neo-liberal reorganization: the initiative was proposed by the PAN, whose business-led leadership promoted a policy in opposition to the wave of privatizations being imposed by the PRI, which controlled the federal government. These agencies have all been successful in ensuring a quality service and expanding their coverage, reducing losses from leaks in the distribution networks. Although their tariff structures are among the highest in the nation (CONAGUA, 2008: 109), their autonomy has enabled them to be more efficient in revenue collection. These systems enjoy the enviable reputation of operating without operational subsidies, although they receive public funds for extending their services to marginal communities.[12]

In most of the rest of Mexico, water services are deficient, inequitably distributed, and offensively inefficient. Political favouritism, obsolete administrative processes, poorly trained personnel, obsolete infrastructure, and a lack of planning, as well as inadequate resources, have created an impenetrable web of secrecy and lack of believable information that makes any diagnosis impossible. This complex system of obstacles also functions as a shield, preventing audits and efforts by technical or financial task forces to try and remedy the situation; this shield is further strengthened by local demands for autonomy and by CONAGUA's insistence on its responsibility for oversight. Any complaints about a lack of transparency or the odious social impacts of the situation are effectively deflected, based on the argument that this is an essential service that would be interrupted by outside intervention. Unfortunately, in many jurisdictions, the problem is not that information is hidden or manipulated; rather, it simply is not available, as the information systems are not in place to allow analysis, much less facilitate planning.

From a social perspective, this situation is aggravated by the lack of equity created by administrative and technical decisions that force the poor to pay more for their water and offer a quality of service inferior to that provided for others in their regions. Unlike the discriminatory patterns that these groups suffer in privatized systems where the service is often provided by tankers or neighbourhood faucets (stand pipes) to marginal neighbourhoods, many poor people must use water from irrigation canals, drainage ditches, or even sewage pipes. Throughout the country, people are forced to buy water from private water purveyors that supply the liquid from tankers at prices as high 'as the market will bear'; these 'pirates', as they are popularly labelled, often enter into conflict with local authorities as they generally get their water from public sources or clandestine (unregistered) faucets. Unfortunately, some peri-urban communities do not even have these choices – they must resort to nearby creeks, forcing women – who are traditionally responsible for water management – to spend as much as a third of their workday on the chores related to supplying the water needs of their families.

Another source of problems is the result of an inequitable distribution of permits for drilling and operating wells by the CONAGUA, which is responsible for this process. Historically, these concessions were issued for specific uses over long periods, frequently for more than a half-century. Today, all water users, including the water boards themselves, must pay for using the liquid because it is constitutionally considered to be the collective property of the nation; the local water boards pay for the water on the basis of the volumes they contract with the CONAGUA, while individual wells are charged a fixed quota for use rights, based on the nature of their concessions. As a result of the changing relative value of water, based on its alternative uses, 'informal' markets have developed among potential users who bid for access from the 'owners', offering a 'rent' to use this water; the new 'owners' then can use the resource for their own profit, regardless of the use for which it was originally granted.[13]

In general, then, water management in the public sector is inadequate. Water is distributed unfairly, with great inefficiency, and without any process of in-

12 As this chapter was being finished the Consultative Council on Water issued a report confirming these findings (Quadri, 2010).

13 An abundant literature documents these transfers and the abuses; newspaper archives denounce these abuses in the acquisition of these concessions that take advantage of a weak legal system and a corrupt administrative structure that permits these informal markets to function at huge social and environmental cost. Privately, high-level officials in the CONAGUA report that there are twice as many wells operating in Mexico City than are legally authorized, and that in other parts of the country the abuse is even greater.

volving or even consulting the users. The financial burden of the system's operation at each level of government is systematically shifted to the public sector – where the regressive structure of the tax system places a disproportionate burden on the poor and the working classes – while the benefits are captured by the large water users. Heightening this discriminatory structure, there are substantial impacts of current water management practices on public health as a result of inadequate administration and technical blindness with respect to these problems.

27.7 Environmental Management and the Treatment of Sewage Waters

Another serious problem that is commonly associated with water management is the lack of knowledge about and concern for the environmental impact of water resources and sewage treatment. In spite of the fact that the CONAGUA has a specialist group that works on issues of environmental degradation affecting most of the watersheds in Mexico, it has failed to convey a sense of responsibility and the need for control by local water boards. There are no systematic evaluations of the impact of the present processes of water use on ecosystems, nor are there environmentally coherent proposals for action in times of natural disasters, which occur with increasing frequency. In the face of a growing water shortage in the urban areas, most government proposals are based on inter-basin transfers and the construction of dams, costly strategies that have occasioned significant environmental damage (Arrojo, 2005; McCully, 2001, 2004). Local authorities in the water sector generally lack the financial and technical means to meet established standards; in spite of these deficiencies, these standards should be taken into account as part of any long-term planning process.[14]

In the case of demand, a 'New Culture of Water' is frequently mentioned, but local water agencies regularly choose to broaden the area in which they collect water to satisfy local demands, instead of improving their traditional practices for watershed management and water distribution. The agencies are negligent in organizing campaigns that promote water-saving technologies or practices for use by their clients or in the design of new buildings and installations. They are also generally remiss in training professionals or modifying building codes to promote this goal. Strategies for rainwater harvesting and recycling are also noticeably scarce, even in the arid areas of the country. 'Public service announcements' are directed at 'blaming the victim' rather than solving the problem. Also worrisome is the lack of any real concern for, or any long-term systematic evaluation of, the impact of the untreated residual water discharges on surface water systems. A notable exception to this generalization is the plan to exchange treated water from the San Luis Potosi area for use in the cooling towers of the nearby thermoelectricity plant, as part of an attempt to solve regional water supply problems.

Mexico is facing a serious challenge from inherited dangers, the result of natural and historical forces that have deposited large quantities of potentially dangerous substances in its watersheds. The centuries of mining and the decades of modern (*sic*) industrial and agricultural production methods have left significant deposits of toxic wastes (arsenic, mercury, dichloro-diphenyl-trichloroethane, better known as DDT, and organo-chloride pesticides) that have filtered into groundwater sources through lixiviation or sedimentation. There is ample evidence that these substances pose serious social risks; however, the government has adamantly resisted specific efforts to legislate against the use of these chemicals or to enforce existing restrictions with regard to their use or their discharge into the environment.[15] Two examples suffice to illustrate these problems:

1. The presence of excessive concentrations of naturally-occurring arsenic in many aquifers as a result of the severe drawing-down of water levels in much of central Mexico. In addition to its substantial presence in Guanajuato, it is found in 40 per cent of the milk produced in Mexico because the water used to irrigate the alfalfa fed to the cows in

14 Aguas de Saltillo conducted a detailed geo-hydrological study of its sources of supply with the help of a group of experts from its foreign partner, Aguas de Barcelona. It reported that with adequate measures for the conservation and protection of these sources, investment in new and costly infrastructure will not be needed in the foreseeable future; unfortunately, the study remains secret, since the firm cites proprietary reasons, raising suspicions about its motives and the nature of its relationship with its majority partner, the local government.

15 Although the subject is old in Mexico (e.g. Restrepo, 1995), it is tragic that even today there are no effective mechanisms to limit the various types of effluents that are labelled as 'non-point pollutants' elsewhere. These are the result of the growing use of non-organic agrochemicals and the noticeably identifiable intensification of mining operations in various parts of the country.

La Laguna, Coahuila has excessive concentrations.[16]

2. In spite of efforts to implant an exemplary international programme to eliminate the discharge of highly toxic chemical effluents from the leather tanning and shoe making industries in Leon, Guanajuato, with support from the Canadian government, and substituting an obsolete technology with a very profitable clean process, after fifteen years the city still suffers the effects of uncontrolled discharges that are channelled into the deeper reaches of its aquifers, with poisonous effects on its ecosystems and the health of its population and workers. Its sewage treatment plants were not designed for these chemical wastes, and its public water management agency – highly regarded by peers in the Mexican industry for its managerial skills and with full support from the local and regional political structure – is incapable of implementing a programme to control this illegal dumping at the point of production by the region's most important industrialists; to implement this control would be a highly desirable strategy for all concerned (a win-win solution) but the 'powers that be' have stymied all intentions for remediation, whilst also effectively tying the 'hands' of the industry research centre (CIATEC) which has effectively acceded to regional demands to declare the pollution problem non-existent. As a result, the region suffers from a costly but ineffective sewage treatment system that imposes a mortal burden on the ecosystem, its aquifers, and the population as a whole (Blackman, 2003; Blackman/Kildegarrd, 2004; Blackman/Sisto, 2003).

On a national scale, less than one-quarter of all urban water consumption even passes through a water purification plant, and a substantial proportion of these plants are not working, according to the CONAGUA. Numerous studies provide evidence that the local agencies cannot effectively ensure the operational requirements nor provide the required preventive or corrective maintenance; nor can they afford to pay for the energy and other operational costs, which often exceed the total local government budgets of the areas in which they are located, because of outmoded technologies, improper or non-existent maintenance, and lack of programmes for the modernization of the infrastructure.

As might be expected, sewage treatment is mandated by law. The larger users are expected to pay sewage fees on the basis of their quality and volume; as a result, some have implemented specific programs to install their own sewage treatment plants to enable them to reuse the water and/or avoid paying the fees.[17] Municipal governments are also obliged to search for solutions for these problems in a context of financial crisis and the 'culture of non-payment' that prevails in most of the country. As a result, there has been a virtual invasion of sewage treatment equipment salesmen, offering 'easy' solutions to the water agencies; these make poor choices in their desperation to find a way out of their financial and administrative problems, without experience or knowledge of available technologies and lacking a culture of environmentalism.[18] Further complicating the search for solutions is the opposition of farmers who currently use the untreated waters for irrigating their crops; the political struggles for control of these waters has prevented the implementation of appropriate and innovative technologies to produce environmentally and economically solid responses. An interesting and important exception to this general pattern is the treatment plant in Villahermosa, Tabasco, which uses a passive biological process in an artificial wetland that was constructed to treat the municipal sewage waters.

In almost all of Mexico, the use and abuse of urban water is leading to environmental destruction with dramatic consequences for the population and

16 Although the source of the arsenic in both areas is from geological formations, its release into the aquifers is a result of the drawing-down of water levels occasioned by over-exploitation.

17 General Motors was awarded the Stockholm Water Prize in 2001 for its well-designed effort to reduce water consumption in its motor block plant in Ramos Arizpe in Mexico; there are many similar examples in all parts of the country, and many organizations boast of these achievements in their corporate advertising.

18 An example of the challenges that the agencies face is the large number of competing sewage treatment technologies. Many of the conventional energy-intensive approaches that generate large volumes of (frequently toxic) waste are favoured by the leading engineering and construction companies in the 'advanced' countries because they are 'turnkey' projects or can be constructed with BOT contracts. In contrast, passive plants that use biological processes are less costly to operate, but require training for community members to ensure optimal operational results; although they promise environmental, social, and financial benefits, the business community and the bureaucracy oppose this choice because it requires specific designs for each site and generates smaller corporate profits.

the health of the ecosystems. In contrast to the principles of the NCW that insist on controlling demand and ensuring environmental quality, the Mexican government continues to submit to the dictates of the international financial community and of the construction enterprises, resorting to inter-basin transfers and large scale construction projects to meet the demand. It continues to ignore the impact of its policies on public health from the multiple sources of contamination from its new industrial and agro-industrial projects that are intensifying sanitary problems while it actively discourages multiple initiatives to implement new technologies that might reverse the present tendencies towards environmental decline (Downs et al., 1999).

27.8 And the People?

Public discussions of water management and the environmental impacts of governmental policy are intensely discouraged and even repressed by the use of the state's police powers. Although decision-making is highly centralized in the *National Water Commission* (CONAGUA), the most important decisions are, in reality, made by other groups. For example, the *Federal Electricity Commission* (CFE) exercises a great deal of autonomy when determining the fate of rivers susceptible of being harnessed for hydroelectricity; the *Secretary of Agriculture* (SAGARPA) plays a dominant role in decisions about the design of irrigation projects, which use more than three-quarters of all available freshwater supplies in Mexico; local water boards attempt to operate as if they were independent with respect to the control of water supplies for urban and industrial users; and, lastly, the business community which operates most of the 'private' wells often proudly flaunts its violations of government regulations that are theoretically designed to stabilize the aquifers. Each, in their own way, is excluding the remaining local groups from participating in the main decisions that affect water allocation, its management, and, as a result, social well-being.

Unfortunately, the social debate about public policy and new governmental project proposals generally face a stony silence and a rapid call-up of the 'forces of law and order' to demobilize any possible collective response. During most confrontations, government agencies offer unfounded promises of compensation, exaggerated claims of benefits from the projects, and repeated assurances of respect for social responsibility. When the state fails to honour its promises, and the people mobilize to protest, they are repressed and jailed, the leaders tortured or assassinated. Occasionally, expressions of international solidarity are effective in guaranteeing support for protecting the independent social movements, as in the case of Rodolfo Montiel, who managed to stop the repeated invasions of the forests in the mountains of Guerrero by the *Boise Cascade* company and who received the Goldman Prize for Environmental activism, but only after being jailed for his activities. In August 2005, the Sierra Club's 'Chico Mendes' prize was awarded to Felipe Arriaga Sánchez, Montiel's partner in these struggles, allowing the continuing violations of human rights related to illegal timber cutting to remain on the national agenda; his sentence was commuted some weeks later. However, impunity is still the dominant feature in the public sector, and unjust jailings are common – especially when indigenous people and peasants are involved in opposing the destruction of ecosystems on which they depend for their very survival.

The bureaucracy has attempted to relegate the water management problem in Mexico to a technical level where public opinion is excluded. Crucial decisions, as the saying goes, are too important to be left to the ordinary citizen and public forums. Even when public discussions and legislative hearings are convened to debate these themes, academics and experienced administrators are called to testify, while ordinary citizens can only wait to voice their complaints about minor issues, the inevitable problems with water quality, or administrative errors. Important decisions about the design of the hydraulic systems, of management of water supplies, and tariff structures are supposed to be left to the experts who merit public confidence, and who should be trusted to represent the people's interests in the exercise of power and resources. Any hint that private interests may be violating the sacred trust of the people is greeted with expressions of disdain or shouts of 'populism' by the power elite.

For the bureaucracy, in this context, any informed opposition or suggestion about the need to consider alternative paradigms is an unacceptable intervention. The 'collective' interest of the nation, defined by the elite at the service of capital, is always more important than the interests of the losers whose rights are being violated in the equation of economic power. Without even considering who is correct, in present-day Mexico everyday practice has led to the careful construction of a national water management system and allocation patterns that are destroying ecosystems, poisoning people, and leaving the country ill-prepared to confront the challenges of moving towards a strategy of sustainable and equitable progress. Decisions are made without plans, with insufficient information or knowledge, and in ways that pit unequal groups against each other; resources are being wasted, people are expendable, and collectively we are suffering the consequences, although some opportunists enjoy short-term benefits.

Again, two contrasting examples are offered that clearly illustrate the challenges that Mexico currently faces:

1. The CFE proposed constructing the second largest hydroelectric project in the country, La Parota, a short distance from the beaches of Acapulco, Guerrero. The project, valued at more than $1 billion, was designed with a reservoir that would extend behind a 192-metre high dam to flood 14,000 hectares and displace some 25,000 people. Instead of trying to negotiate credible terms of compensation and programmes to stimulate regional development, or to consider alternative models for environmental management and energy generation in discussions with the affected communities, the government tried bribing community leaders while jailing the most intransigent and killing several protesters. After years of struggle, the concerted mobilizations and shows of international solidarity had their effect, forcing the government to cancel the project for the foreseeable future.
2. The proposal to create a mixed public-private company for water services in Saltillo appeared quite popular when it was announced in 2001. The bidding process was organized by Arturo Anderson, a consulting firm that became notorious for having not reported the financial precariousness of one of its clients, Enron, which failed with far-reaching consequences for the financial system in the USA. One of its clients then won the contract in Mexico. The new company decreed 'irregular' price increases, closing off any public discussion of its policies that had led even its majority partner – the local government – to express concern. Questions about technical matters and expressions of social discontent were brushed off in the light of the substantial improvements in service quality that led to a positive report from the public opinion polls that were conducted. The local legislature conducted an audit on the basis of energetic complaints from a small group of technically competent citizens that raised a number of serious doubts about the way in which the company had exceeded its authority to raise the real cost of service; the questioning continued, moving the national Consultative Water Council to create a local Water Observatory as a permanent body to oversee the situation. In a region where there are no mechanisms for conciliation among the parties, where there are no impartial mediators, and the political atmosphere is charged with mistrust and instability, the question of the firm's transparency and fairness remains open to question.

27.9 Conclusions

Unlike many other countries in Latin America, neither the government nor civil society has been able to implement a successful programme for the reform of urban water administration. In spite of numerous protests and innumerable mobilizations in response to their poor administration, the agencies charged with delivering adequate and accessible service have failed in their task; the present structure is also incapable of protecting the ecosystems from which the water comes. The main obstacle facing the country in its attempt to achieve this object is the unwillingness of the public sector to encourage or even permit citizen participation in the discussion and oversight of the management of public services, including urban water. Numerous problems such as the lack of financial solvency, regulatory capability, and training, foil efforts for improvement. These obstacles will continue to be insurmountable if citizens are not permitted to participate in their solution.

Experience with foreign participation in local service contracts is not particularly encouraging and offers little consolation for the advocates of privatization. Although they have implemented important service improvements and improved revenue collection, many doubts still exist about the use of questionable financial practices that lead to higher profits at the expense of the consumers. In the case of Cancun, people continue to ask how Ondeo managed to get the government bank to finance its investment in the project, while the accusations against the management practices of the local team from Aguas de Barcelona (heightened by the refusal of the municipal authorities to exercise their supervisory functions as majority owners of the venture) confirm fears about the ability of international capital to do as it pleases. The case of Aguascalientes reinforces the call for creating adequate independent regulatory structures to protect the public interest. The experience of Mexico City has proved to be atypical, since it strictly limits significant corporate profits in a situation where there is a workable model of supervision that has enabled the City to reach the expected performance levels.

On the other hand, the exceptional cases of independent public sector agencies operating efficient services offer evidence that the government is capable of reorganizing itself to serve the public. In their own ways, each of these water boards has proved that it is possible to achieve considerable improvements, generating a confidence among the users that has led to a willingness to pay their bills regularly. Unfortunately, unresolved issues with regard to ecosystem management continue to accumulate and have become particularly serious in Leon, Guanajuato and Torreon, Coahuila. These are only two examples of the very important environmental damage that is accumulating in virtually all of the water service areas, be they private or public. They are a challenge that the national government has not accepted as a priority and does not appear to be able to meet; the lack of political will and the low level of technical and financial capabilities are a growing obstacle.

Unfortunately, most of the public sector agencies are poorly prepared to meet the needs of their clients or to plan to meet their future demands. The current scheme of decentralization does not appear to be well suited to a country lacking the technical preparation and the required financial resources and plagued by obsolete administrative systems. It offers an incubator in which ambitious politicians can appropriate control of the system for their own personal gain, with no concern that there might be some effective counterbalance to insist that the benefits be used for the wellbeing of society.

In contrast, there are some exceptional examples of initiatives that have created highly original and effective mechanisms for solving local problems. Some of these examples have been documented for Mexico (Barkin, 2001). Evidence from other countries suggests the importance of stimulating local initiatives to control better public sector activities; in this context, the experience of collaboration with public agencies that have been successful in providing public services has proved quite productive (Hall et al., 2009). These experiences not only reflect the ability of oversight and the possibility of dynamic conflict resolution processes, but frequently also contribute to building efficient governmental agencies that provide public services to marginal populations (Satterthwaite et al., 2005). With appropriate support, they ensure a more equitable distribution of the benefits. Perhaps one of our most pressing tasks should be to explore the feasibility of new models for assuring an adequate water service in Mexico.

In 2006, the public sector proved woefully unprepared to host the IV World Water Forum in Mexico and has not demonstrated that it is better prepared today to meet the challenges of assuring the Mexican people the quality of service they demand and deserve. This is evident in the public sector's continuing opposition to recognizing the right to water as a basic human right, manifested once again in the official Mexican position at the V Forum in Istanbul in 2009.

Official intransigence provokes unnecessary conflicts, intensifies popular unrest, and obliges the citizens to raise their level of organized violent protest (beautifully portrayed in the film *13 Pueblos en Defense del Agua, el Aire y la Tierra–13 villages in defence of the water, the air and the land* – directed by Francisco Taboada (2008) and awarded the Bronze Cross at the film festival held during the Istanbul V World Water Forum in 2009); it also excludes informed dialogue and questioning with regard to important technical, environmental, and social issues.

The bureaucracy boasts about local standards while the official discourse continues to be so superficial that foreign observers consider it to be frankly shameful. In the years following the IV World Water Forum, local groups in Mexico have deepened their understanding of the gravity of the situation and insisted on the urgent need to be informed about the serious problems they face. Their initiatives towards create new spaces to express themselves are multiplying; the *Coalition of Mexican Organizations for the Right to Water* (COMDA, its Spanish acronym) is a valuable example that complements the increasing academic capacity to explain the deepening water crisis and to help the population confront the challenges (Esch et al., 2006).[19]

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28 The Growth of Water Demand in Mexico City and the Over-exploitation of its Aquifers

Jorge A. Morales Novelo and Lilia Rodríguez Tapia

28.1 Introduction[1]

Mexico City – with a population of more than 20 million people – is confronting one of the most serious short-term water resource problems in the world. This is due to an inability to supply water to several of its zones, as well as to a reduction in supply during drought periods. The medium- and long-term problem is severe because supply, which is inelastic, cannot meet a growing demand. The impressive urban growth of Mexico City has encouraged a water policy that has over-exploited groundwater bodies within its boundaries; since the local supply is insufficient, the city now extracts ground and surface water from adjacent basins. These basins include the Lerma and Cutzamala Basins. Currently, the risk is that this complicated and costly system will collapse, with grave environmental, economic, political, and social consequences.

Total water extraction in Mexico City exceeds the natural availability of water in the basin by 1.73 times, putting extreme pressure on the aquifers of the Valley of Mexico, and making the city one of the most hydrologically over-exploited regions in the world. If the city continues to grow at the present rate, extraction will exceed availability by a factor of 2.25 by 2030, and this will result in still greater pressure unless drastic measures are taken to reduce consumption. To confront this problem, the development and implementation of a new policy is suggested, in which demand is adjusted to availability instead of seeking new and distant water sources to increase supply.

It is important to implement a hydrological policy that promotes wastewater recycling, something that has important precedents in other cities of the world. Recycling is cheaper and would enable sustainable water management. Reduction of leaks in the distribution system is another way of increasing supply; it is estimated that water leaks account for 35 per cent of water use. Eliminating leaks would represent a significant gain.

Finally, an important way to reduce demand is to eradicate the waste of water by domestic and industrial users. Water consumption in the capital is the highest in the country despite the fact that residents live in the most over-exploited basin in the country, a situation that is partly explained by the fact that water rates are very low and do not reflect either scarcity or supply costs.

The management of hydrological resources in Mexico City is one of the most serious short- and medium-term challenges. In the short run, we need to solve water shortages in several zones of the city that are exacerbated during drought periods. In the medium term, we need to face constraints on water supply capacity in order to meet increasing water demands. In particular, this chapter examines the *Valley of Mexico Basin* (VMB). This region involves Mexico City or the so-called *Metropolitan Zone of the Valley of Mexico* (MZVM).

The growth of the MZVM has been supported by a hydrological policy based on the over-exploitation of water resources. That policy emphasizes the necessity of meeting the water needs of an increasing population and of economic growth at any cost. However, the policy has reached a danger point. At present, the hydrological system is at risk of collapse, and this situation raises important environmental, economic, and social issues. The basic hydrological problem consists of a growing imbalance between water supply and demand, mixed with negligence on the part of the authorities in adjusting this gap between supply and demand. Thus, the severity of the crisis demands the development and application of a new hydrological policy that will encourage and emphasize

1 Keywords: over-exploitation of aquifers, water shortages in large cities, demand-based hydrological policies, urban growth and water demand, water supply limits in large cities.

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_28,

water demand management in the MZVM region instead of water supply.

This chapter is divided into four sections. The first section demonstrates the limitations of water supply in the Valley of Mexico, while in the second the levels of water demand for the year 2004 are reviewed. In the third section the high degree of pressure on the aquifers in the Valley of Mexico and in the Lerma and Cutzamala basins, where there is high demand, are described. In the fourth section, water demand projections for 2025 and 2030 are presented. The chapter concludes that if the present pattern of water consumption persists, it will be impossible to satisfy the demand. Finally, reflections are offered on the need to change hydrological policy to a policy based on efficient water use that will modify the present water consumption patterns. This could be achieved through technological innovations, price increases, and other measures that should send pertinent signals to users on the severity of water shortages in the Valley of Mexico.

28.2 Water Availability in the Valley of Mexico

28.2.1 A Present Scenario of Absolute Constrains

The XIIIth *Hydrological and Administrative Region* (HAR), known as the Valley of Mexico[2], is made up of two hydrological basins: the Valley of Mexico Basin and the Valley of Tula Basin. Each basin constitutes a subregion with the same name. Mexico City is located in the Valley of Mexico Basin (or subregion).

Mexico City is the economic centre of the country, with an urban population of 20.1 million (INEGI, 2010) and an area of 7,854 km^2; it has a population density of 2,450 people/km^2. This density places Mexico City as the second most populated metropolitan area of the world, after Tokyo in Japan.

The Valley of Mexico Basin is the source of the water resources for Mexico City (figure 28.1). This area has been defined by its geographical characteristics and does not correspond to any political delimitation. In contrast, *the Metropolitan Zone of Mexico City* (MZMC) is an area in permanent expansion; its limits are determined by a continuous movement of people through economic development. So far, the MZMC includes the Federal District and 70 municipalities from the states of Mexico, Hidalgo and Tlaxcala. Nevertheless, some authorities suggest the definition of the MZMC should be extended to include other municipalities within the state of Hidalgo. For instance, the government of the state of Hidalgo has proposed to incorporate 29 additional municipalities within the MZMC, where 50 per cent of the total local population is concentrated in an area estimated at 25 per cent of the state of Hidalgo. This new delimitation was accepted at the 5th Plenary Session of the Executive Commission of Metropolitan Coordination held on 12 March 2008. By this agreement, the municipalities incorporated will share resources from the Metropolitan Fund. This configuration of the MZMC presents a problem in adequately managing water resources and basin levels.

According to a UN classification (WRI) water stress is

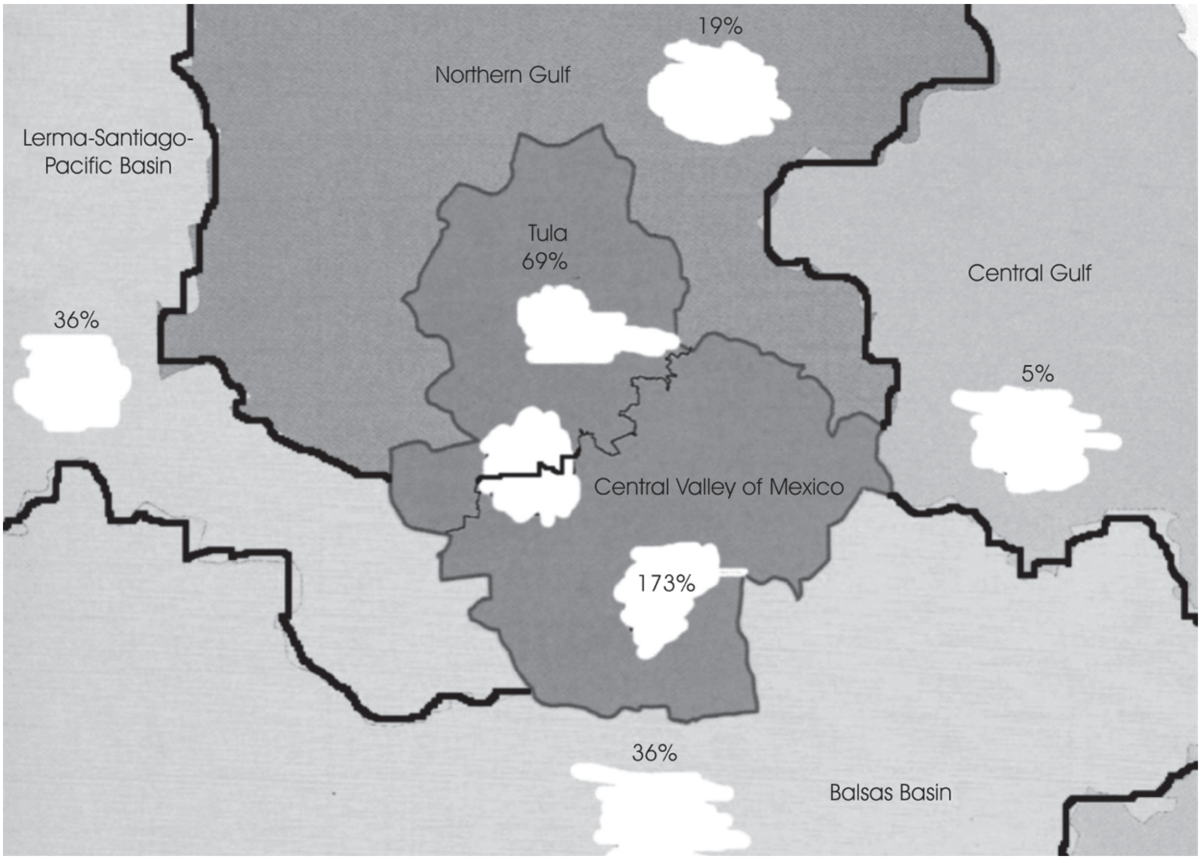
- *High*: Water stress > 40 per cent;
- *Medium to high*: 20 per cent < Water stress < 40 per cent;
- *Moderate*: 10 per cent < Water stress < 20 per cent;
- *Low*: Water stress < 10 per cent.

The degree of pressure[3] measures the vulnerability of water resources. Figure 28.1 shows that the degree of pressure in the Valley of Mexico Basin is 173 per cent, which represents a very high degree of pressure on these aquifers. According to the UN classification (figure 28.1), the figure of 173 per cent implies an extreme pressure on water resources in the region.

2 The demarcation of *Hydrological and Administrative Regions* (HAR) is based on river basin boundaries and takes municipal boundaries into account in order to facilitate the production of socio-economic information. There are 13 HARs in the country. The Hydrological and Administrative Region "Valley of Mexico" is characterized by being the least extensive in surface area but at the same time it is the most populated. Population density in the region is 26 times greater that the national average. Likewise, it accounts for 25.5 per cent of GDP (estimated for 2006; SEMARNAT, 2008).

3 The degree of pressure is defined as the relation between the total volume of concessional water and average water availability. When the degree of pressure is greater than 40 per cent, severe pressure on the resource exists. Another measurement is Falkenmark's index, which classifies water availability according to categories. Less than 1000 m^3/inhabitant/year implies extreme water shortages (WRI, 2000).

Figure 28.1: Water stress in the Valley of Mexico (2004). **Source:** Prepared by the authors based on data from SEMARNAT (2005: 37).



28.2.2 Natural Water Availability in the Valley of Mexico Basin

Figure 28.2 shows the annual natural cycle of water for the Valley of Mexico: rain supplies an annual precipitation of 6,828 hm^3, of which three-quarters returns to the atmosphere through processes of evapotranspiration; this amounts to 4,901 hm^3. The remaining water is distributed to surface water (241 hm^3), groundwater or groundwater recharges (751 hm^3) and drainage (937 hm^3).

The natural availability of water is a standard international measurement that consists of the water that is infiltrated into the ground and is stored in the aquifers of a basin or region per annum. It constitutes a measurement of potential supply. In the Valley of Mexico Basin the average natural water availability per annum is 1,688 hm^3 (table 28.1). This volume constitutes the renewable water that may potentially be used to meet water demand in the region.

Groundwater infiltration has decreased due to changes in soil surfaces caused by the rapid growth of new buildings and paved road surfaces. Thus, it is necessary to halt the reduction of water infiltration and to design mechanisms which facilitate the process of infiltration and consequently increase the availability of natural water in the region.

Table 28.1: Mean natural water availability in the Valley of Mexico Basin (2004). **Source:** Prepared by the authors based on data from SEMARNAT (2005: 36).

Origin	m^3/s	hm^3/year
Mean surface run-off	29.7	937
Groundwater recharge	23.8	751
Mean Natural Availability	**53.5**	**1688**

28.2.3 Permanent Water Demand Growth in the MZMC

The water demand in the MZMC is satisfied by the Valley of Mexico Basin. According to the *Federal Public Register of Water Rights* (FPRWR)[4] the water de-

Figure 28.2: Hydrological cycle in the Valley of Mexico Basin. **Source:** Prepared by the authors based on data from SEMARNAT (2005: 36, 2004: 42-43).

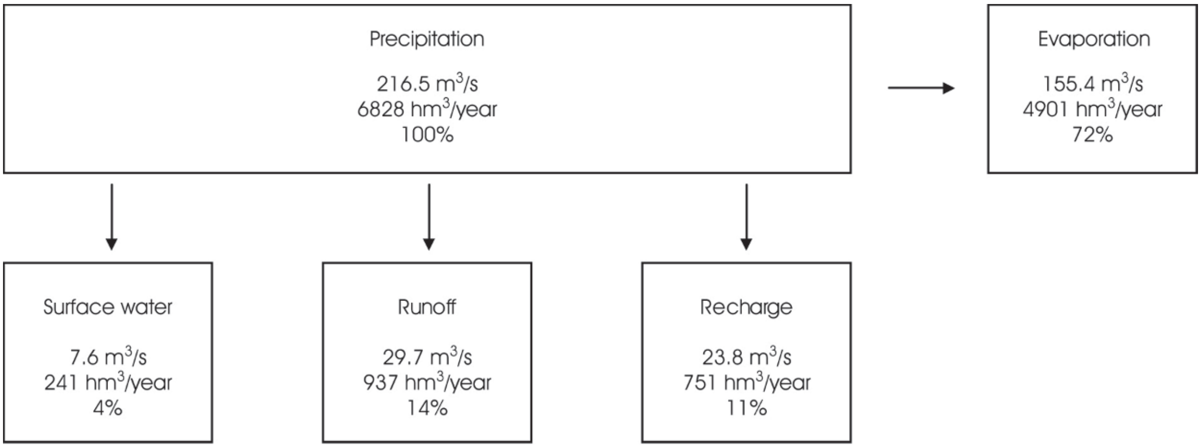
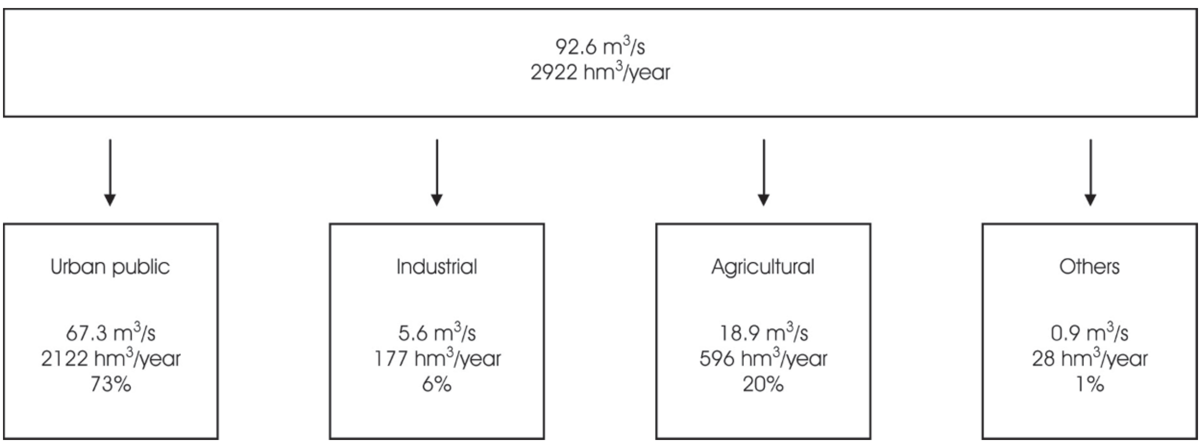


Figure 28.3: Water uses in the Valley of Mexico by user type. **Source:** Prepared by the authors based on data from SEMARNAT (2004: 81).



mand in 2004 was 2,922 hm^3. Figure 28.3 shows the water uses in the basin in 2004. Urban public demand was the most important use with a volume of 2,122 hm^3, followed by agricultural demand with 596 hm^3, industrial demand using 177 hm^3, and finally other uses with a volume of 28 hm^3.[5] The agricultural demand is consumed outside the MZMC.

4 The FPRWR registers water volumes given or allocated to different users within the country; it registers allocated water volumes and uses.

5 The *National Water Law* (NWL) clearly states the order of priority in case of emergency, extreme water shortage, over-exploitation, or use of water reserves. In any of these cases, the top priority is domestic use (Chapter IV, article 13). The NWL (Congreso de la Unión, 2004) also considers changes in the rank order when all parties agree, including the *National Water Commission* (CONAGUA).

28.2.4 How is Excess Demand Satisfied in Relation to the Availability of Natural Water?

The total water supply in the Valley of Mexico Basin has an annual average volume of 2,922 hm^3 (table 28.2), which is equal to demand. About 67 per cent of total supply (1,943 hm^3) is extracted from surface and groundwater, while water reuse amounts to 12 per cent (359 hm^3) and the remaining supply is imported (21 per cent). Four-fifths of the demand is extracted from the Valley of Mexico Basin and the remaining fifth, amounting to a volume of 622 hm^3, is imported (table 28.2).

Most water demand in the Valley of Mexico is met by the water resources of the basin, but due to the urban sprawl, the water authorities have decided to import water from other basins, and this has marginal-

Table 28.2: Average water withdrawal in the Valley of Mexico Basin (2004). **Source:** Prepared by the authors based on data from SEMARNAT (2004: 81).

Supply Sources	hm^3/year	%
Withdrawals in the Valley of Mexico Basin	1943	67%
Import	622	21%
Reuse	359	12%
Total withdrawal	**2922**	**100%**

ized the promotion of the reuse of waste water. Thus, although the use of treated residual water is limited, it represents a potential source of supply that could reduce the pressure on water resources. There are several problems associated with importing water from adjacent basins. As residual water is an alternative solution to water shortages in the Valley of Mexico Basin, water authorities should seriously consider it.

28.2.5 Water Over-exploitation in the Valley of Mexico Basin (VMB)

In 2004, the total water withdrawal in the Valley of Mexico Basin was 1,943 hm^3, of which 241 hm^3 or 12 per cent was drawn from surface water and 1,702 hm^3 or 88 per cent from groundwater. The annual natural recharge of the aquifers in the VMB is only 751 hm^3. This shows that the aquifers have been over-exploited by 951 hm^3 per annum to meet the demand (table 28.3). Thus, 1.27 times more water is withdrawn in the VMB than the annual natural availability. This estimate highlights the degree of water over-exploitation. As the annual water withdrawal is greater than the natural recharge, this means that each year water is withdrawn from groundwater storage. This over-exploitation generates several problems. Not only is there ground subsidence in the urban areas of the Valley of Mexico, but the quality of the water withdrawn is reduced, as it contains mineral particles from the subsoil.

Table 28.3: Aquifer over-exploitation in the Valley of Mexico Basin (2004). **Source:** Prepared by the authors based on data from SEMARNAT (2004: 43)

Origin	m^3/s	hm^3/year
Natural Recharge	23.8	751
Groundwater withdrawal	53.9	1702
Over-exploitation	**30.1**	**951**

The over-exploitation of groundwater is the most serious problem for future regional development. Clandestine wells exacerbate the situation. The authorities should stop granting more water extraction licences. On the contrary, however, during the year 2009 when user demands rose because the amount of imported water fell, the water authorities of Mexico City even granted licences for the exploitation of new wells, further exacerbating this severe problem.

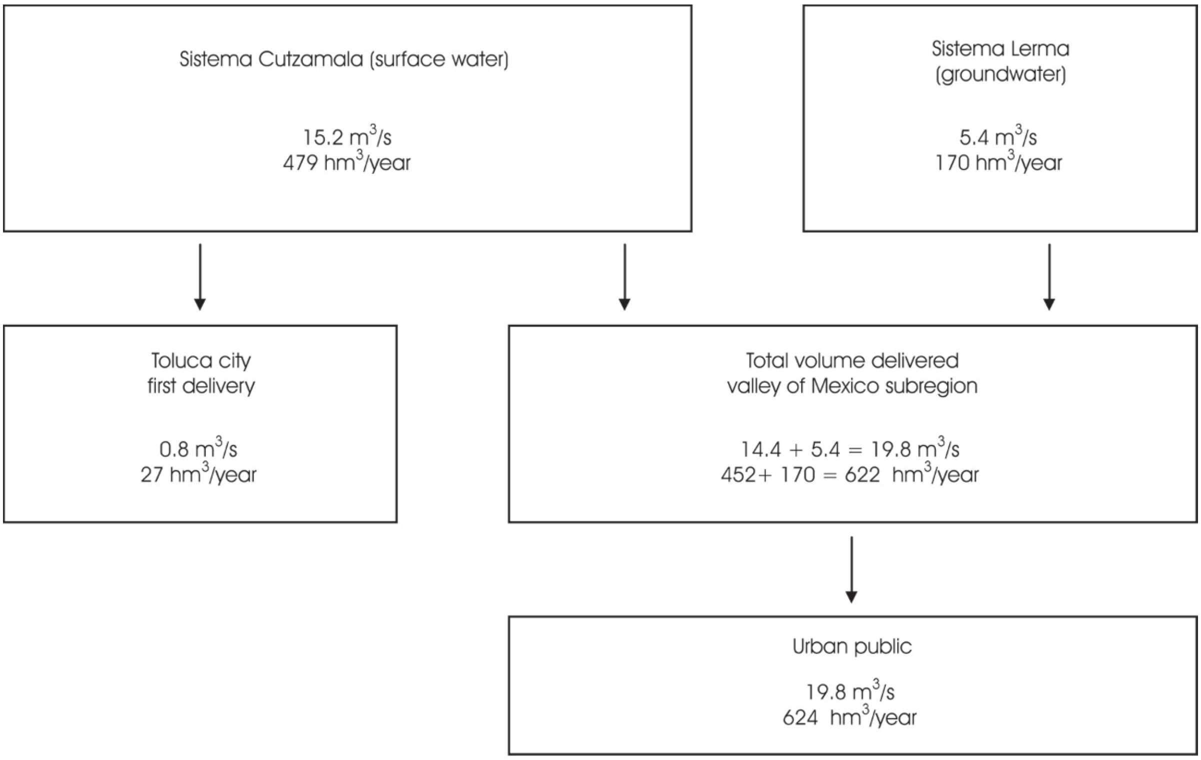
28.3 Water Importation from Adjacent Basins

The Valley of Mexico Basin is surrounded by five neighbouring basins, namely: Lerma, Cutzamala, Amacuzac, Libres Oriental, and Rios Tecolutla. The closest basins to the MZMC are Lerma[6] and Cutzamala[7]. Both contribute to the water supply in the area (figure 28.4). However, because of the rapid growth in demand, the feasibility of importing water

6 Water transportation from the Lerma River to the Valley of Mexico has been considered since 1929. In 1940, the authorities began analysing the project. Eventually, in 1952, water transportation from the Lerma River into Mexico City was possible. Lerma has lakes that are 300 metres above the altitude of Mexico City. At this stage, the first groundwater collection system was established. Five wells of varying depths (50–308 metres) were dug in order to extract groundwater. The second stage of the Lerma system was developed between 1965 and 1975, when 230 wells were built. The Lerma Basin is supplied by the Lerma River which originates in the Pacific mountain range. Subsequently, this water is introduced to Mexico City. Finally, the water is discharged into the River Tula and the Moctezuma and Panuco Basins.

7 The construction of the Cutzamala system, the most important work of water supply in Mexico, started in 1976. Its purpose was to transport water from the Cutzamala River to Mexico City. Before its construction, the river was only used for energy generation. The main problem faced by the construction of the system was the considerable height difference that existed between the Cutzamala River and the Valley of Mexico. It was necessary to develop a pumping system to transport the water to a more elevated location. During the first stages of the project, water was brought from Victoria by an aqueduct. The second and third stages of the project included the construction of both a water treatment plant and a central aqueduct. This project concluded in 1992. In terms of investment, there is still a fourth stage planned to transport water from the Temazcaltepec River and store it in the Valle de Bravo dam.

Figure 28.4: Water imports to the Valley of Mexico. **Source:** Prepared by the authors based on data from SEMARNAT (2004: 82).



from other basins to the Valley of Mexico has been studied.

One-fifth of the water demand in the Valley of Mexico is imported from the Lerma and Cutzamala Basins (622 hm^3). Water transportation is possible from two important works of hydraulic infrastructure: the Cutzamala system, located in the XII HAR 'Lerma Santiago'; and the Lerma system, located in the VIII HAR 'Balsas'. The former supplies water from surface water, while the latter supplies water from groundwater.

28.4 Water Reuse as an Alternative Source of Water Supply

There is another potential supply source for the MZMC, water reuse, amounting to 359 hm^3 in 2004. This fraction could increase if investments were made in treatment plants and if a market for treated water could be developed to reduce the pressure on water availability. Initially, water should be reused for industrial purposes. However, it would also be convenient to introduce it to all sectors, including domestic consumption. For the agricultural sector, reuse should only be allowed for treated water that meets current water norms and standards. This is crucial as the reuse of waste water in agriculture has produced serious health problems for the population in the past.

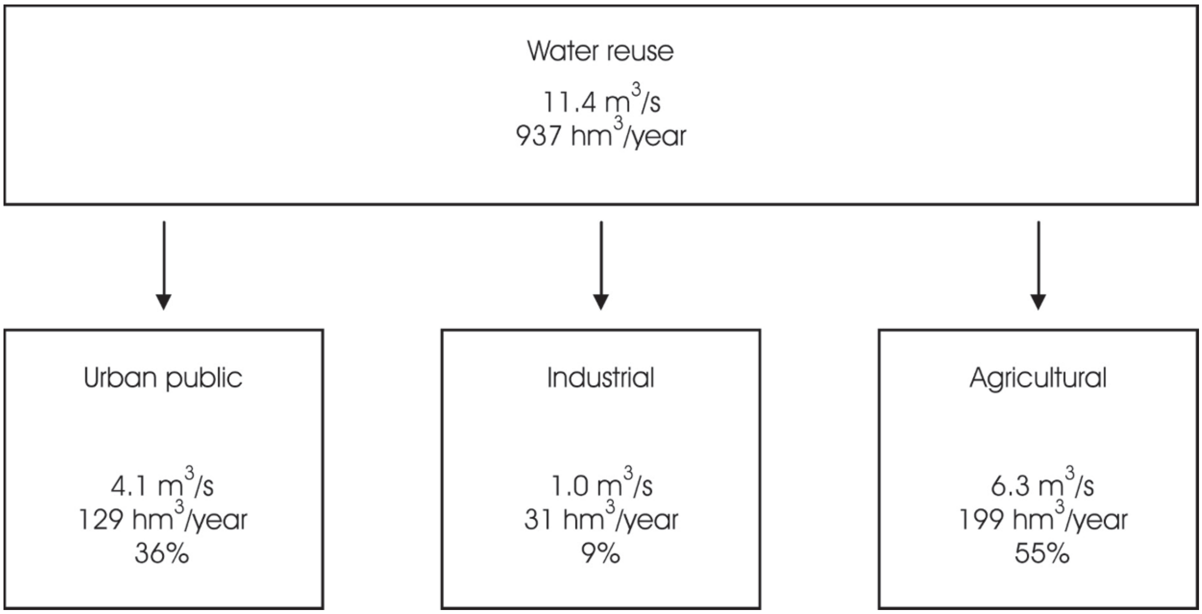
Figure 28.5 illustrates the consumption of reused water in 2004. The agricultural sector was the main consumer with a volume of 199 hm^3, while the industrial sector reused a water volume of 129 hm^3. This suggests that there is a potential market that should be developed for economic activities in all sectors. This seems a convenient alternative that would solve the problems caused by constraints on first-use water withdrawal.

28.5 Hydrological Stress Scenarios in the MZMC for 2025 and 2030

28.5.1 Scenarios of Limits

The future population growth of the Valley of Mexico, especially in the MZMC, signals an increasing demand for water. Here a scenario is presented for 2025

Figure 28.5: Water reuse in the Valley of Mexico by sector. **Source:** Prepared by the authors based on data from SEMARNAT (2004: 81).



and 2030 which evaluates the risks of maintaining the same rate of water withdrawal. This scenario assumes that the increases in water demand will be determined by the water consumption patterns observed during 2004.

The population growth rates in the Valley of Mexico are stabilizing (table 28.4). In the 1990s the growth rate was 1.71 per cent, whereas it was 1.03 per cent for the period 2000–2005. This reduction is chiefly explained by population behaviour in the MZMC. In the 1990s, the population in the MZMC increased at an average rate of 1.64 per cent per annum, whereas the rate was only 0.86 per cent per annum for the period 2000–2005. The population increase in the Federal District (Mexico City) was 0.27 per cent in the period 2000–2005. In contrast, population increases in the municipalities that do not belong to the MZMC but which are part of the Valley of Mexico showed an opposite trend. During the last five years, the population in the state of Hidalgo grew at a rate of 2.61 per cent, in Tlaxcala the growth rate was 1.75 per cent, and it was 1.59 per cent in the municipalities of the state of Mexico.

The total water withdrawal projection for 2025 and 2030 was estimated using the five-year period growth rate. However, if population growth rates keep falling over the following years, the projection for water withdrawal might be an overestimate. This scenario assumes that there will be no changes in the economic or natural conditions, nor in technology,

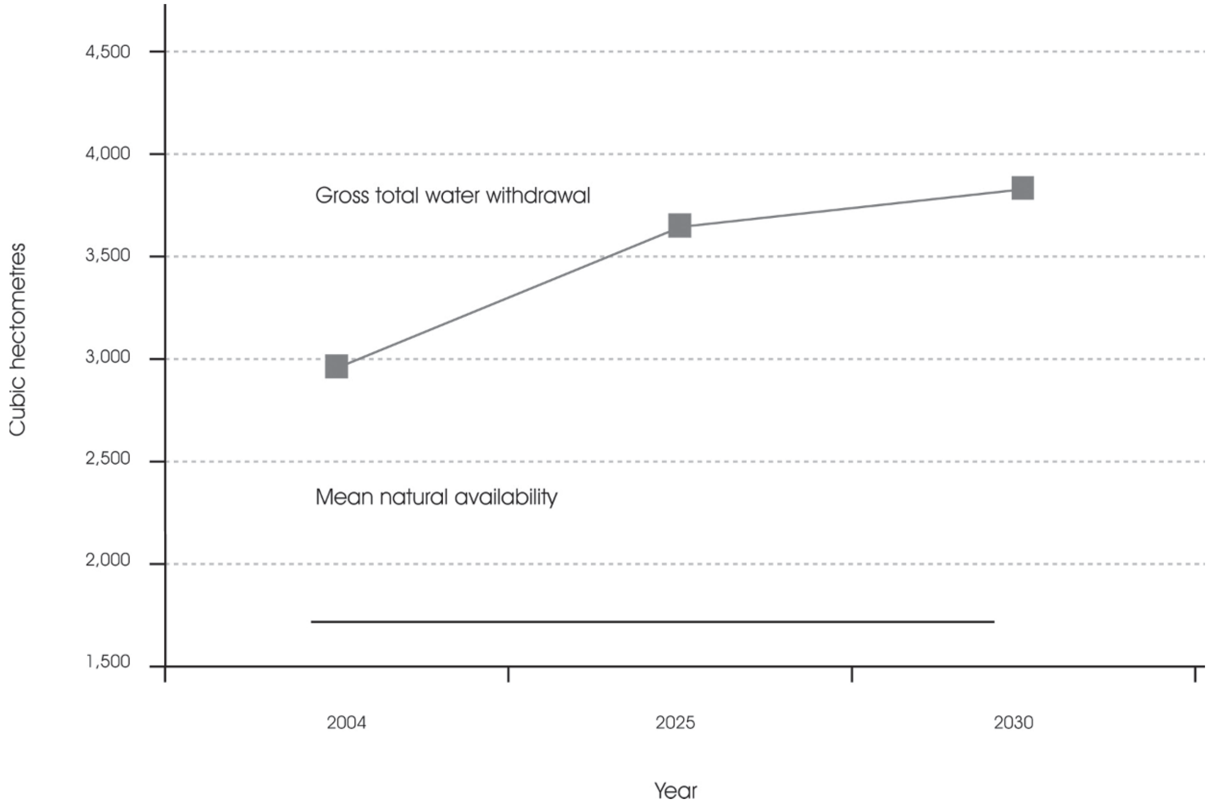
Table 28.4: Population growth rate in the Valley of Mexico and in the Metropolitan Zone. **Source:** Prepared by the authors based on data from SEMARNAT (2005: 36).

Zone	Growth rate (1990-2000)	Growth rate (2000-2005)
Valley of Mexico Subregion	1.71%	1.03%
Mexico City (Federal District)	0.44%	0.27%
State of Mexico	2.95%	1.59%
State of Hidalgo	2.55%	2.61%
State of Tlaxcala	2.06%	1.75%
Metropolitan Zone of the Valley of Mexico*	**1.64%**	**0.86%**
Mexico City (Federal District)	0.44%	0.27%
State of Mexico	2.92%	1.39%

*) Including the 16 political districts that constitute Mexico City and 35 municipalities in the state of Mexico.

hydrological policy, fees (at real value), and in other issues related to water management. Besides this, constant availability of water is assumed, which is a reasonable assumption since it depends on the hydrological system and constitutes the water supply indicator. Therefore a constant water availability vol-

Figure 28.6: Gross total water withdrawal and mean natural availability in the Valley of Mexico: 2004-2030. **Source:** Prepared by the authors based on data from SEMARNAT (2005: 36).



ume of 1,688 hm^3 per annum is assumed. Figure 28.6 shows the total water withdrawal for 2004 and the volume projections for 2025 and 2030, as well as the natural availability in the Valley of Mexico Basin.

Figure 28.7 shows the water supply projection by component from 2004 to 2030 in the region of the Valley of Mexico. The high withdrawal volumes in the Valley of Mexico Basin are noticeable. The estimated water withdrawal volume for 2030 is 2,536 hm^3, which cannot be withdrawn from surface water, much less from groundwater sources.

Imported water is the second source of withdrawal; in 2004 it accounted for a water volume of 622 hm^3. According to estimates, the water to be imported for 2025 was projected to amount to 771 hm^3, and for 2030 it would be 830 hm^3. What is at stake here is whether such imported volumes are feasible. The main problem is the high cost of importing each cubic metre, besides the geographical constraints of water in the adjacent basins that must be taken into account. Nevertheless, the water authorities have chosen this alternative for facing the water crisis in the MZMC.

The third source of the water supply in the Valley of Mexico is reused water. This is a feasible alternative as it is cheaper and sustainable. The reuse of residual water only accounted for 12 per cent of the total water supply in 2004. According to projections, the growth rate of reused water would equal the growth rate of the population by 2025. Thus, the withdrawal volume for 2025 would be 445 hm^3, and 469 hm^3 for 2030. But this growth would be insufficient to reduce the pressure on water, and so the growth rates for reused water must be greater than the growth rate of the population.

As far as groundwater is concerned (figure 28.8), as there has already been an over-exploitation of the aquifers amounting to 751 hm^3 for the year 2004, the over-exploitation for 2025 is projected at 1,360 hm^3, and at 1,471 hm^3 for 2030. Clearly, such a high water withdrawal is impossible.

Figure 28.7: Total water stress on the hydrological resources in the Valley of Mexico subregion. **Source:** Prepared by the authors based on data from SEMARNAT (2004: 81).

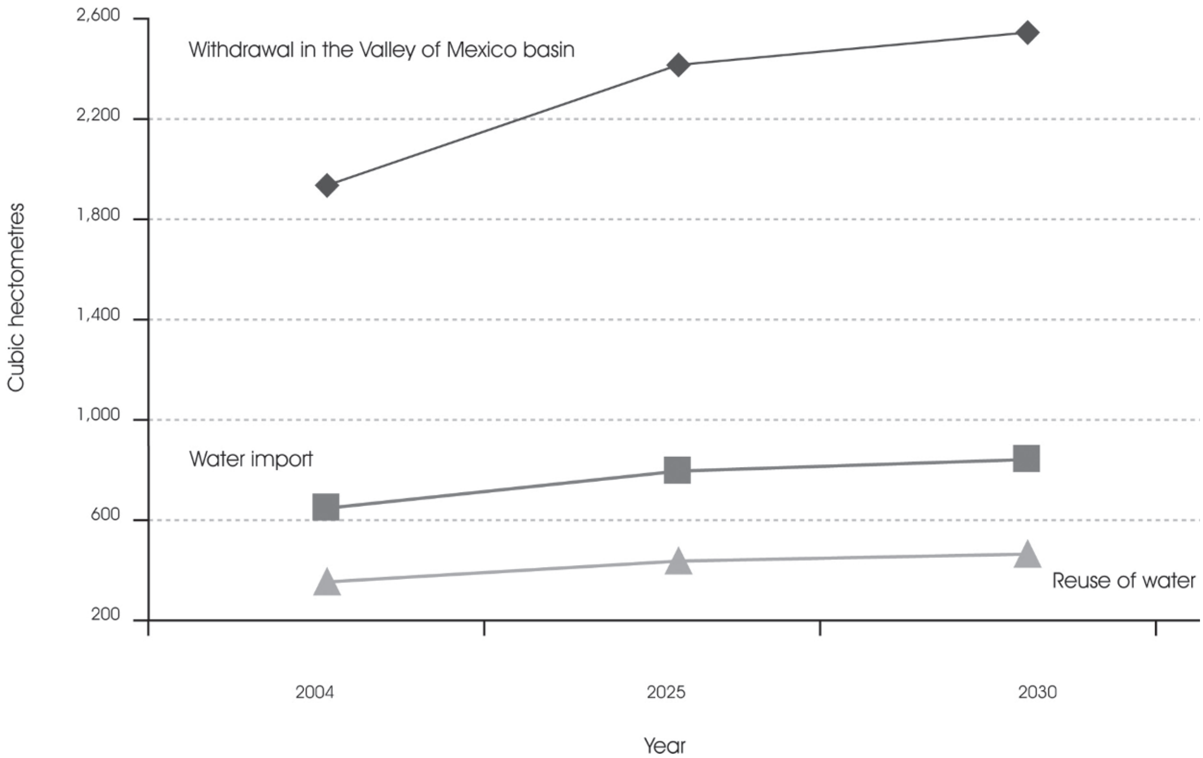


Figure 28.8: Projection for the over-exploitation of the aquifers in the Valley of Mexico Basin. **Source:** Prepared by the authors based on data from SEMARNAT (2004: 43).

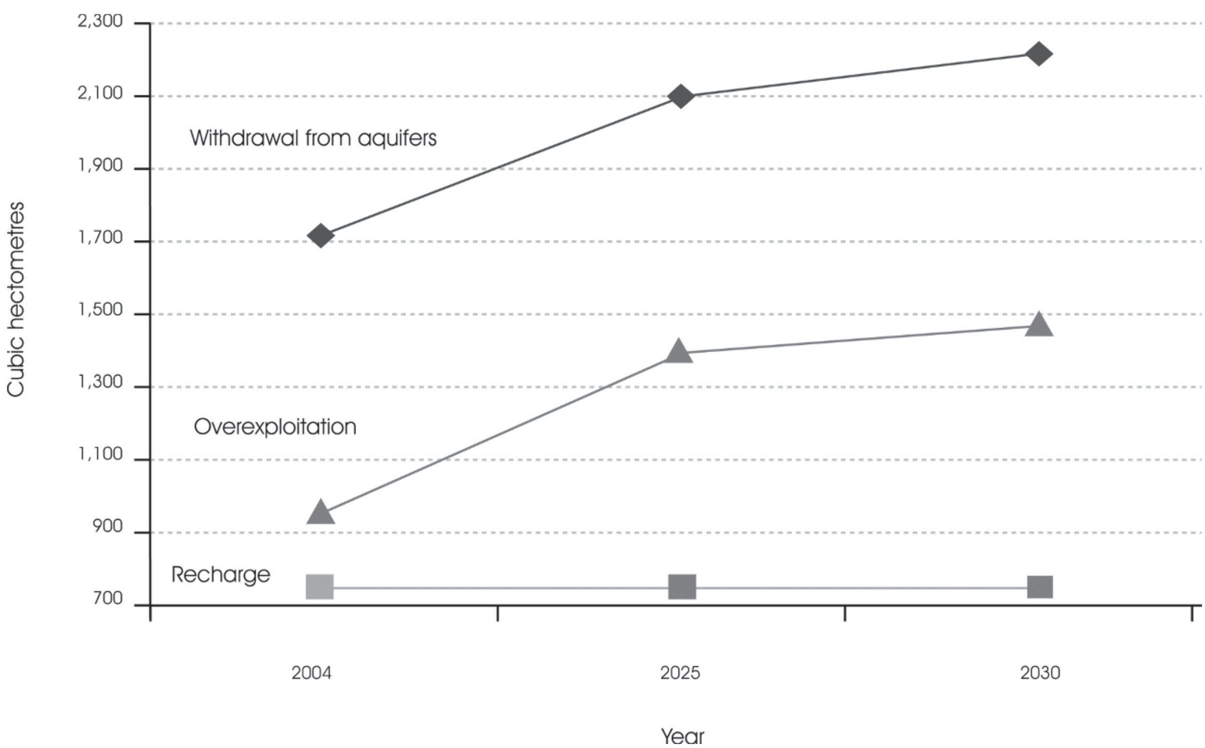
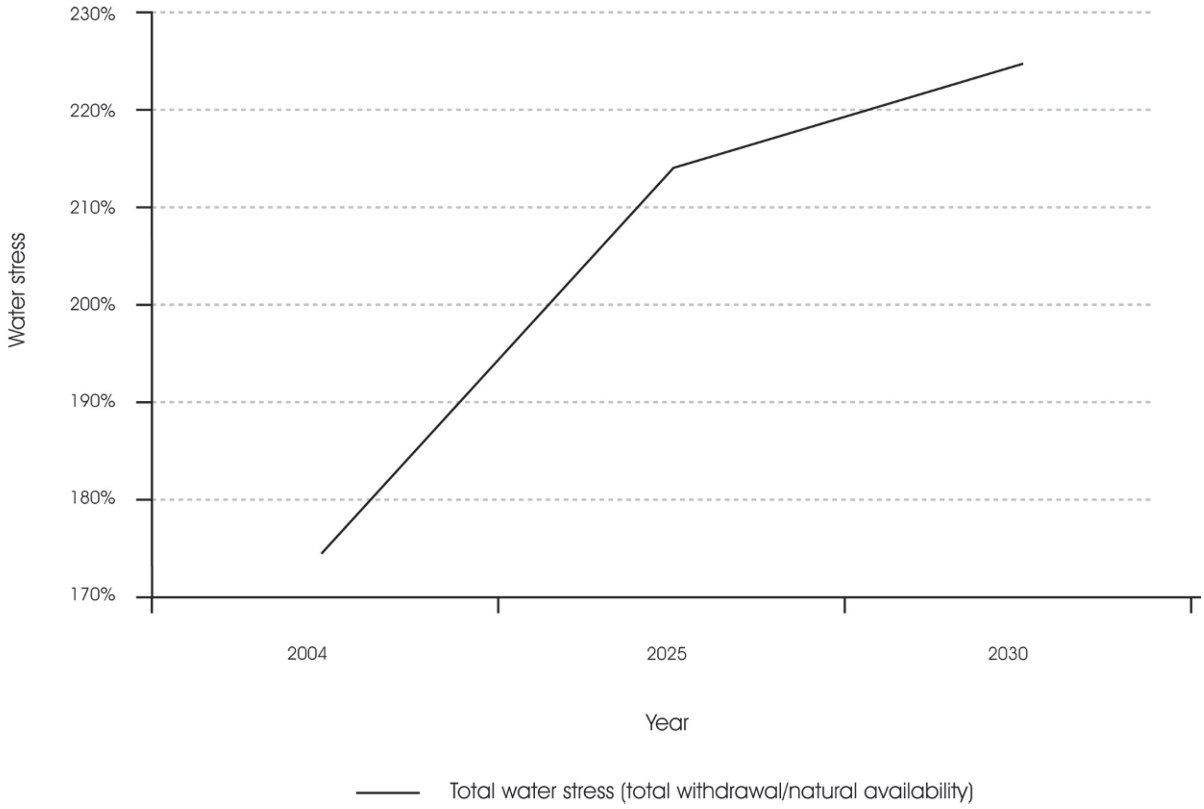


Figure 28.9: Total water stress on the hydrological resources in the Valley of Mexico subregion. **Source:** Prepared by the authors based on data from SEMARNAT (2005: 37).



28.5.2 Pressure on Hydrological Resources and Unsustainable Management in the Valley of Mexico Basin

Figure 28.9 illustrates the degree of the pressure on hydrological resources. An acceleration of the pressure in the Valley of Mexico can be observed. In 2004 the degree of pressure was 173 per cent, and for 2030 projections indicate a level of 226 per cent. This situation indicates a transition from a condition of very high pressure to a level of pressure that implies the exhaustion of all hydrological resources in the region.

28.6 Concluding Remarks

The water system that supplies water to different users within the Metropolitan Zone of the Valley of Mexico is at grave risk of collapsing. Given this diagnosis, a scenario can be envisaged where there will be increasing water shortages in different areas of Mexico City. The current hydrological model has reached its own limits. The water supply system is already overexploited and if the water demand keeps rising, water withdrawal will face even more serious problems, since the possibility of increasing supply in the short term is not available. The alternative, importing water from other basins, is politically complicated, expensive, and unsustainable. On the one hand, it is impossible to increase the level of over-exploitation of local groundwater. Exploitation of the aquifers has reached a level of 173 per cent, which is classified as a very high degree of pressure. This current degree of pressure presents a warning of the many risks associated with withdrawing more water from areas within the Valley of Mexico Basin, as well as of the poor water quality that this might provide.

On the other hand, importing water from the rivers Lerma and Cutzamala also has its limitations, so that no considerable growth in the water supply can be expected in this region. Over time the supply capacity of these water resources has declined. The dams of the Cutzamala system only stored 50 per cent of the system's capacity in 2009. This explained the temporary water shortages and water rationing policies in Mexico City during 2009 and 2010. The alternative, increasing water imports, is neither a feasible nor a sustainable solution to facing the problems of water scarcity in the MZMC. This chapter does not therefore consider it as an alternative.

The problem of water supply is a very serious issue for the present and the future; it requires action together with policies to reduce water demand. Such policies are certainly not popular and might affect the popularity of existing governments and politicians, but the severity of the problem requires measures in this direction.

Population growth in the Valley of Mexico has slowed down and so allows us to seek a sustainable hydrological policy. However, in the scenario reviewed in this chapter, this factor is not sufficient to provide reasonable benefits. According to the projections for 2025 and 2030, the limits of a sustainable withdrawal will be exceeded, implying serious physical damage in the hydrological system due to over-exploitation. It is therefore necessary to find new schemes of water demand management and public policies that include the repair of damage to the aquifers and restoration of the natural ecosystem.

Water withdrawal in the Valley of Mexico Basin exceeds 1.73 times the average natural availability. This points to a very high pressure on the aquifers of the Valley of Mexico and makes this region one of the most over-exploited regions in the world.

Importing water has been a partial solution to water shortages in the basin. The Cutzamala system transports surface water via a long and expensive route into Mexico City. This source of supply also faces over-exploitation and is expensive; its costs are supported with large public subsidies. As well as this, there is a growing possibility that these hydrological resources will be needed for local consumers for their own and exclusive consumption. So far, Mazahua women have launched a movement to prevent more water from their regions being exported into the MZMC. They have demanded the right to use it exclusively in their area. They have also demanded compensation for the ecological damage in their region due to the negative effects of water extraction for economic activities.

The development of industrial activities that require first-use water should be avoided in the MZMC. These industries should be relocated to regions with more water supplies. Human consumption of water depends on water imports for 30 per cent of its supply, and only 6 per cent of the demand for human consumption is met by re-used water.

There are also medium-term constraints on water imports. A good alternative water supply is water reuse; but the authorities have not studied this alternative seriously enough. Although the industrial sector has drawn on recycled water as part of their water supply, further development of this source of water is needed. In the MZMC there are several industrial activities that can incorporate recycled water into their production processes. Hence, water reuse can be considered an important source of water in the future.

The elasticity of the water supply is small and represents an insurmountable obstacle. Reuse of water is therefore the only alternative to increasing the water supply. This alternative is used by many other cities around the world; it is cheaper and allows sustainable water management. Likewise, it is important to repair water leaks throughout the distribution system. It has been estimated that 35 per cent of total water volume is lost during transportation. Repairing these leaks would automatically increase the water supply by 35 per cent.

Current behaviour by water users in the MZMC demonstrates a lack of knowledge about the severity of the water scarcity crisis. Domestic users waste large volumes of water. The MZMC has the highest water consumption rate per capita in the country, while the Valley of Mexico Basin is the most over-exploited basin. This relationship between the waste of water and its over-exploitation is possible because the price of water is very low. This price reflects neither the water shortage crisis nor the high supply costs. So far, neither the government nor the operational organizations have sent appropriate signals to consumers to promote efficient water use, such as adjusting water prices to reflect the real costs of supply. It can be expected that an increase in water prices will decrease the water demand for domestic use.

A sustainable and sustained water management requires urgent investment to encourage the collection of rainwater, the development and maintenance of infrastructure, and efforts to rehabilitate the ecosystem. This would increase the water supply in the basin. Moreover, it urgently requires a public policy limiting the demand for water, given the real supply constraints in the Valley of Mexico Basin.

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Part V Public Policy, Institutions and Legal Aspects

29 Reflections on the Magdalena River Master Plan in Mexico City

Arsenio Ernesto González Reynoso and Itzkuauhtli Zamora Saenz

29.1 Introduction[1]

The trend in river restoration is towards the development and implementation of multi-purpose management projects. Besides environmental and hydraulic objectives, these projects promote new goals linked to political, cultural, social, and economic issues. Following this approach, the problem goes beyond the solutions offered by traditional hydraulic engineering directed exclusively at confining rivers and treating wastewater. The development of multi-purpose projects accounts for a) the role of multiple agents in the planning process, b) the search for interdisciplinary solutions, and c) inter-sectoral planning and intergovernmental coordination.

At present, some policies imposed from above to restore water bodies will generate resistance from different social groups, even if these initiatives are well-grounded in order to seek environmental benefits for society as a whole. If policies to rehabilitate and to restore water bodies lack mechanisms for social participation, ensuing popular movements and social actions may hamper projects and even halt initiatives, at a tremendous cost.

Interdisciplinary integration is a vital aspect in the rescue of water bodies, even though sometimes this integration is discursive and is interpreted as amalgamating the basic components proposed by each discipline, contrary to the basic axiom of complexity 'the whole is more than the sum of its parts'. Effective integration of all scientific disciplines involves seeking solutions in the search across disciplinary boundaries in order to develop feedback and effective communication channels in the process of building transdisciplinary knowledge. In this regard, one indicator is the development of a *meta-language* across disciplines and among involved scientists.

Finally, this chapter discusses how such initiatives could be developed and implemented simultaneously by different governmental agencies. Often the best projects fail due to a lack of cooperation among the government agencies. Following a collaborative team effort, this chapter addresses the process of integrating the Master Plan of an Integral Sustainable Management of the Magdalena River Basin in Mexico City (also called the Magdalena River Master Plan).

In this process, different academic centres of the National Autonomous University of Mexico (UNAM) participated, such as the Faculties of Architecture and Sciences and the Institutes of Geography, Engineering, and Ecology, all coordinated by the *University Programme on Urban Studies* (PUEC). Funding was allocated by the Ministry of Environment of Mexico City (SMA-GDF) from November 2007 until December 2008. Overall, more than seventy researchers participated in the project, ranging from full-time researchers with doctoral degrees down to undergraduate students whose theses were related to the socio-environmental system under study.

The development of the Master Plan took place within an international framework directed towards the design of public policies for the cleansing of surface water bodies, especially urban rivers. Through conferences, seminars, workshops, and symposia, the scientific community interested in the topic exchanged experiences and empirical evidence in order to strengthen theories, methods, and techniques that can help better develop and implement restoration and rehabilitation projects. Guided by a multi-objective approach, the problem goes beyond the solutions offered by traditional hydraulic engineering directed exclusively at confining rivers and treating wastewater, in order to incorporate cultural, political, social, and economic benefits (Riley, 1998).

The process of integration in the rescue of an urban river encompasses three spheres of action, namely a) the role of multiple agents in the planning process, b) the search for interdisciplinary solutions,

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1 Keywords: restoration of urban rivers, interdisciplinarity, integrative methodology, social participation, governance.

Ú. Oswald Spring (ed.), *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*,
Hexagon Series on Human and Environmental Security and Peace 7, DOI 10.1007/978-3-642-05432-7_29,

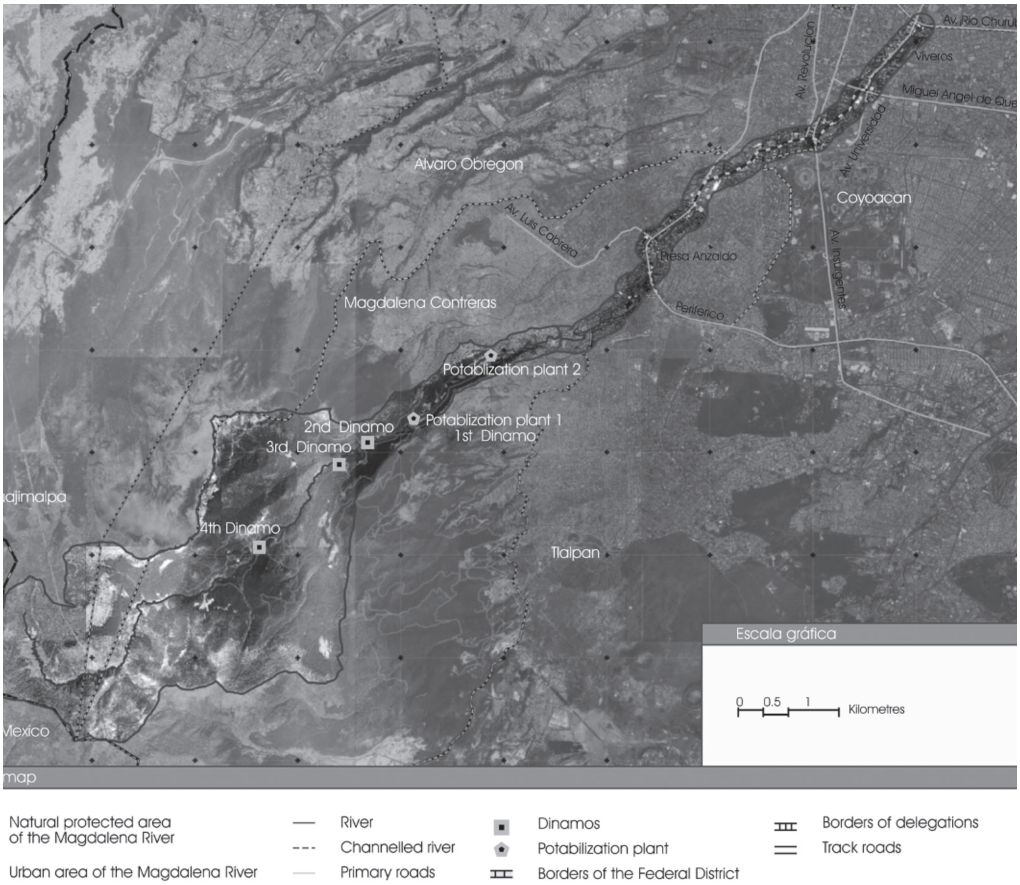
Figure 29.1: Location of the Magdalena River basin. **Source:** Master Plan of Integral Sustainable Management of the Magdalena River Basin in Mexico City (SMA-GDF, UNAM, 2008: 9).

and c) inter-sectoral planning and intergovernmental coordination. This chapter covers these fields of work and knowledge integration.

The area studied was the basin of the Magdalena River, located in the Sierra de las Cruces mountain range to the south-west of Mexico City. This basin borders on the basin of the Eslava River in the south-west, and on the basins of the Rivers Hondo, Mixcoac, Barranca de Guadalupe, and San Miguel in the north-west, all of which together with the Magdalena River form the Churubusco River.

The bed of the Magdalena River is 28.2 km long, 14.8 km of which are conservation soils. A part that is located in the city was directed into a pipe (4.6 km);

Figure 29.2: The planning area of the Magdalena River Master Plan. **Source:** Master Plan of an Integral Sustainable Management of the Magdalena River Basin in Mexico City (SMA-GDF, UNAM, 2008: 16).



the culvert is in a main road that connects Revolution Avenue and Insurgentes Avenue. The complete area of the river system includes the five political sub-districts within Mexico City of Cuajimalpa, Magdalena Contreras, Tlalpan, Alvaro Obregon, and Coyoacan (figure 29.1).

Its hydraulic infrastructure includes 57 gabion dams, two water purification plants with a total capacity of 410 litres/second, the Anzaldo dam, and the west interceptor that expels water from various rivers into the south-west of the Vaso de Cristo. Despite these installations, only this river enters the urban zone of Mexico City as a natural watercourse.

In total, the planning area comprises 3,500 hectares and includes 107,294 people. The criteria used to delimit the basin were of two types. While topographical criteria were used in the natural area, the urban area was delimited with a strict urban-landscape criterion, selecting a buffer zone of 250 metres on each side of the river. This was because in the urban area the river is fully integrated into the sewage system and it receives refuse liquids and waste matter (figure 29.2).

This delimitation also tells us something important about the rescue of urban rivers: the planning area is not predetermined. Modifying the natural conditions of the basin requires the use of various criteria that enable a better understanding of the functioning of the system (Stanton, 2007). The criteria will be different in each particular case. Although reviewing a number of urban river rescue case studies is very useful for becoming acquainted with the general trends and guidelines, it is essential to keep the specificity of each project in mind.

The rescue of urban rivers has great potential in Mexico. Various urban river sanitation programmes have been identified at the state level, but they are insufficient to face the great number of rivers that are polluted and of the rivers at risk of disappearing. We hope the model we have developed, with its strengths and its weaknesses, proves useful for other local initiatives.

29.2 Objectives

The main objective of this chapter is to present the methodology that was used in the preparation of the master plan for the rehabilitation of an urban river in Mexico City (the Magdalena River Master Plan). Although this methodological model was designed for the rehabilitation of urban rivers, it may also be useful for other types of water or socio-environmental sanitation projects (lakes, beaches, urban forests, etc.). The other specific objectives that will be addressed in this chapter are:

1. to outline the way in which interdisciplinary work following cross-boundary problems was achieved;
2. to emphasize civil participation in planning as a strategic driver for the middle- and long-term sustainability of the project;
3. to highlight the importance of effective coordination with several government agencies in order to find out about projects that are currently under way, as well as to retrieve information regarding previous studies and projects;
4. to demonstrate the process that the academic coordinators of the Magdalena River Master Plan followed in the integration of knowledge originating from different scientific disciplines, government agencies, and civil participation; and
5. to promote debate on the scientific and urban-environmental planning spheres surrounding the design and execution of methodological models that favour the development of urban river rescue plans and programmes.

29.3 Methodology

The initiative of rescuing a river involves distinct social actors and groups. Each of these groups has its own perspective regarding what the river means; for example, it can be considered a city's natural patrimony, a community's cultural heritage, and a source of ecosystemic services, sewage, or even an unwanted element of the urban landscape. There is hardly a consensus surrounding the type of intervention it needs: restoring it, treating its waters, making it into a tourist attraction, directing it into pipes, etc. (Findlay/Taylor, 2006). Social representations are diverse and may even be antagonistic.

Territories are not something preset or given. Rather, they are a dimension where material and natural elements converge, linked to symbolic and cultural elements. Thus, developing the Master Plan for the Magdalena River necessitated identifying a general typology of actors and social groups who were involved in the process and would sooner or later have to interact and reach a consensus.

Key actors were grouped into three main spheres. An intense dialogue and knowledge generation process would ensue with each. These were:

a.) social groups linked to the basin on an everyday life, with a series of interests and opinions surrounding the river (dimension of social participation);
b.) researchers constructing the river as an object of knowledge based on a vast array of technical and scientific disciplines (dimension of interdisciplinary research); and
c.) bureaucratic and political authorities, who agreed that the river should be rescued (dimension of multi-sectoral government).

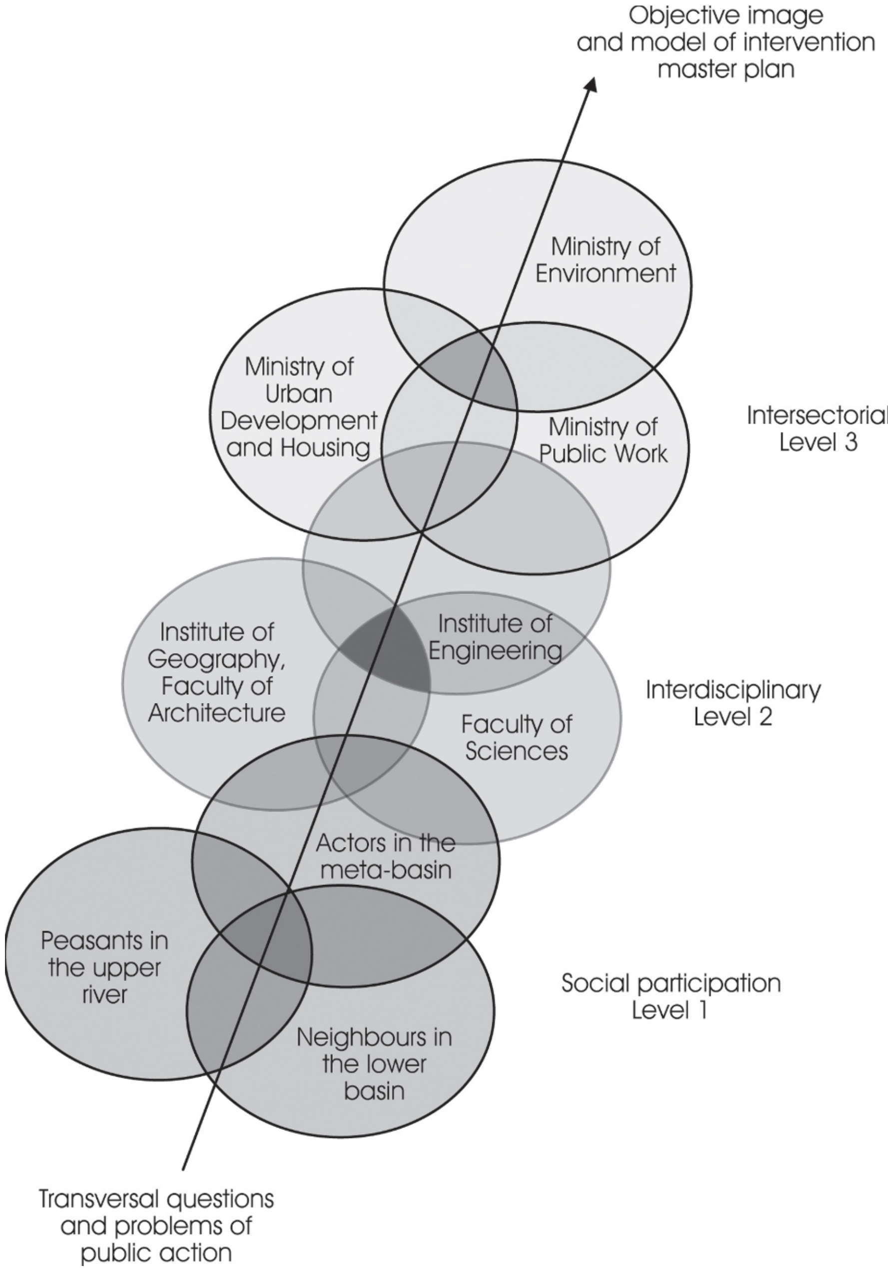
This integration process is graphically illustrated in figure 29.3.

As can be seen in figure 29.3, none of the three dimensions is monolithic and homogeneous: the interests of the various social groups are highly differentiated according to their relationship with the river (rural actor vs. urban actor). Scientists work with languages and paradigms that often have no common ground (biology, engineering, geography). Also, government offices have programmes that often lack the coordination that would make them effective within a given territory, especially if government rules are being observed by different political parties at different levels (Perló/González, 2005).

Therefore, the methodology used in this chapter is based on four integration processes: one for each of the aforementioned dimensions (three in total), plus a general fourth process, which simultaneously integrates the other three. The vector used in this project is congruent with the triad that governs most planning projects: diagnosis, target image, and proposed solution (Southern New Hampshire Planning Commission, 2002).

- The diagnostic stage was the integration of existing knowledge and the generation of new knowledge about the particular problems being studied.
- The second stage involved designing a target image. This target includes desires, expectations, and ideas surrounding the future of the river. Often, this stage of setting objectives is undermined as it is considered as a "declaration of good intentions", an intangible exercise that has nothing to do with what is to be achieved. However, in our

Figure 29.3: Integration process for the Magdalena River Master Plan. **Source:** Developed by the authors (2009).



experience, this stage was crucial in envisaging targets and reaching a consensus about the objectives. All the participants, citizens, scientists, and politicians, expressed their will and without a genuinely consensual target image, the steps to define the actual proposal would have been very difficult.

- The third stage was the production of proposals and prescriptions. These are geared towards regulating practices and setting up specific projects in order to reach pre-set targets. In this case, for the Magdalena River Master Plan, proposals were organized as strategies and lines of action. Strategies defined the core organizing axes, whilst lines of action set the control measures and their applicability.
- Below will be shown how knowledge was generated in each dimension, as the dynamics and problems that characterize these are of particular importance.

29.3.1 The Dimension of Social Participation

If we view social participation and interest groups historically, two parallel structures have emerged in Mexico. The first stems from the political system and includes parties and local, state, and federal election representatives. The second deals with the hydraulic system and includes officials working with water, water services, and sanitation concessions at the local or federal level. Both structures are insufficient, as interests, territorial representations, and aspirations go beyond them. Thus, in order to restore urban rivers, we should note that identifying social agents and territories is not a *natural* or a given process; it calls for a theory and a methodological model that encompasses all the agents that play a role in each particular case.

At present, policies imposed from above aimed at restoring bodies of water cause resistance mechanisms to be created in all groups, even if these initiatives are well grounded and seek environmental benefits for society as a whole. If policies for the rehabilitation and restoration of bodies of water lack mechanisms for social participation, ensuing popular movements and social actions may hamper projects and even put a halt to initiatives, at a tremendous cost (Dourojeanni/Jouravlev, 1999).

At this stage, it is important to stress that the university teams were not accountable for the work. The government authorities were responsible for planning and organizing the participatory planning workshops. Nevertheless, the university team conducted a meticulous follow-up of information processing by the local communities.

Five working sessions took place, chaired by the consulting team hired by Mexico City's Ministry of the Environment to facilitate the workshops. In the meetings, different viewpoints were exchanged in order to guarantee representations of the plurality of actors located across the basin. It was agreed to use the SWOT[2] analysis technique so that the viewpoints of all the different citizens would be integrated.

During February and March 2008, five workshops took place across the basin: two with property owners of 'communal land' in La Magdalena Atlitic; one with the merchants of los Dinamos and the inhabitants of La Magdalena; one with the inhabitants of the Jardines del Pedregal quarter; and one with the inhabitants of Chimalistac and Francisco Sosa in Coyoacan.

Working sessions sought to identify problems and critical pollution zones as identified by owners and inhabitants of the 'communal land'. Also, strategies and proposals for maximizing strengths were favoured, in order to overcome weaknesses and prevent the emergence of threats. A target image was designed from the perspective of local actors.

The information generated in the workshops was classified into distinct spheres of action (for example, problems and proposals for cleansing the river, conservation of the forest, landscape and architectural projects, etc.), and civil proposals were forwarded to the scientists' team in order to provide them with professional feedback. A detailed revision of civil proposals by scientists was a cornerstone in providing a legitimate and consensual platform for developing the Master Plan. These workshops were also useful so that all the social actors concerned with the river's future could network with each other. The creation of social networks surrounding a project can become an important driver for collective action, as well as a civil mechanism of observation and oversight of the government (Otto/McCormick/Leccese, 2004).

29.3.2 Dimension of Interdisciplinary Research

The establishment of interdisciplinary research teams is not neutral, as the experience of the scientists in projects focusing on practical or political solutions is highly varied. Some scientific fields lie closer to the search for practical solutions, whereas others are oriented towards empirical evidence or theoretical and methodological issues. This is the first aspect to keep in mind when interdisciplinary research teams are being coordinated. To be successful, it is imperative to make it explicit that this research is mainly directed at political and not at academic goals. The study responds to citizens' interests and to the need to rescue a river, and it involves the design of public policies. This does not mean that scientists must abandon their data collection methods and scientific rigour; on the contrary, it is scientists who have the appropriate tools and training to provide expert advice for the planning and execution of such projects.

Based on this premise, the next step involves articulating the opinions of all researchers in order to reach a scientific diagnosis of the socio-environmental system of the Magdalena River basin. The integrative approach utilized was interdisciplinary, following the definition of complex systems analysis by Rolando García:

2 Acronym denoting Strengths, Weaknesses, Opportunities, and Threats (SWOT analysis technique).

> Whereas multidisciplinary research adds together the contributions each investigator provides – rooted in their particular discipline – surrounding a general problem that may be analyzed according to different outlooks, interdisciplinary research presupposes the (prior) integration of these different outlooks in order to delimit a research problem. [...] This means conceiving research problems as systems with inter-defined elements, calling for the coordination of disciplinary outlooks that ought to be incorporated in an integrated approach for their study (García, 2006: 33).

The scientific research team at UNAM incorporated experts from the following disciplines: hydrology, biology, geology, geohydrology, economic geography, social geography, environmental engineering, hydraulic engineering, landscape architecture, urban studies, law, economics, social anthropology, and sociology. This multidisciplinary research team converged in 11 plenary workshops to discuss the socio-environmental system, its processes, and the prescriptions the Master Plan should contain. In all meetings, the integrating team was responsible for proposing the discussion technique, setting a preliminary integration agenda, and posing cross-boundary questions in order to orient working sessions.

Interdisciplinary workshops were organized in the following stages:

- preliminary concepts and method of integration;
- integral diagnosis;
- target image;
- general and particular strategies;
- zoning; and
- triggering projects.

Besides the workshops, it was important to make joint fieldwork to both the rural and urban areas. These activities facilitated the exchange of opinions concerning conditions in the basin as well as the transfer of experience from those teams who had previous knowledge from working in the area. Some researchers were linked with other teams, especially those teams with whom they shared related topics; in this way, costs were minimized and data collection was maximized. Also, these joint trips facilitated liaison between researchers, enabling shorter meetings for discussing specific issues without the need to summon all parties involved.

Finally, the integration team was also put in charge of developing and integrating the cartography. Each discipline used different scales and work platforms. For example, geographers used smaller scales in cartographic systems in order to integrate metadata, while architects used larger scales that allowed for greater detail and allowed software to visually illustrate the project. This way of differentiating by scales is inherent in the methodological plurality of the various scientific and technical disciplines. However, homogenizing criteria are necessary in order to make data cross-disciplinary, so that thematic maps can be developed that can become a powerful heuristic tool for the analysis of territorial processes.

29.3.3 Dimension of Inter-sectoral Government

A recurrent complaint by citizens and scientists is lack of information from the authorities. In the development of a Master Plan it is a commonplace to ask for past projects, data, or measurements. The lack of response to these requests may be due to any of three causes: a) lack of organization and systematizing of studies and projects in government offices; b) lack of experience by new authorities who are unaware of past archives (this is usually linked to the first cause); c) information protected by confidentiality clauses. Also, it is often the case that studies, plans, and projects do not circulate within different government offices, which accounts for the eventual loss of information and strategic knowledge as well as a wasteful duplication of resources.

Besides this, there is another aspect to bear in mind related to the inter-sectoral dimension of the government. Time does not stop while research is being conducted in a given territory. Different government offices continue to implement their particular strategic plans and actions. Often, if researchers are not aware of these plans, they might either interfere with programmes or recommend similar ones.

For the Magdalena River Master Plan, the authorities of the Ministry of Environment in Mexico City (SMA) created a team to work exclusively on the administration of the project. This decision facilitated the work of the team as a whole, and an office was established to request information and materials, and to communicate and implement decisions. Also, the coordinating team at the Ministry of Environment in Mexico City was in charge of liaison with other government offices. They were also essential in the organization of the workshops in which researchers and authorities took part. For example, for topics relating to the water infrastructure, meetings were held with government officials and the authorities at the municipal water utility of Mexico City (SACM); topics relating to natural resources and soil conservation involved meetings with the *Natural Resources Commission*

(CORENA); and in the field of the project's architecture and urban landscape, the coordinating team of the Ministry of Environment was in charge, given the profile of its members.

The meetings were especially useful in defining projects and strategies. The experience of public officials and mid-level bureaucrats should be recognized in the process of integration as they possess a practical expertise that becomes essential when projects are being implemented (relations with civil society, budgeting, and success and failure measures for planning). We can illustrate this with a concrete example. Initially, one proposal by researchers for cleansing the river was to introduce a series of water treatment plants along the basin. However, in the workshops with the local water authorities, it became evident that although the proposal would be ideal in theory, in practice it was impractical because of budget limitations and problems linked to the plants' operation and maintenance. Following a debate between scientists and government officials, an agreement was reached; three water treatment plants with greater capacity would be adopted.

Government offices are not monolithic; government action in a given territory is neither uniform nor set *a priori* (Perló/González, 2005). In the meetings held with local water authorities it was interesting to observe the diversity of attitudes towards the rescue of the river, often involving diametrically opposed viewpoints, methods, and goals. Without these meetings it would have been impossible to reach a minimum consensus base in order to enable the master project to be designed. In the immediate future, it will remain indispensable that the coordinating authorities of the *Ministry of Environment in Mexico City* (SMA) continue informing all the ministry's employees about the project, as well as federal authorities (SEMARNAT, the Federal Ministry of Environment, and CONAGUA, the National Water Commission), as well as the authorities in charge of the five political sub-districts where the river is located (Cuajimalpa, Magdalena Contreras, Alvaro Obregon, Tlalpan, and Coyoacan).

There are other cases where rescue of urban rivers necessitates other types of organizational schemes at the metropolitan, inter-state, and international levels (for example, rivers that run across state or federal borders). Nevertheless, linking multiple social actors and government officials is a built-in aspect of any river rescue plan. Such projects require collaboration, negotiation, and consensus, from the design through to the implementation stages (Weatherford, 1990).

29.3.4 Dimension of Transversal Integration

Parallel to the integration of information and knowledge generated in each of the previous dimensions, there is a fourth dimension of transverse or cross-boundary integration, where equilibrium was sought between all actors and social groups. There was no apodictic or conclusive knowledge; on the contrary, dialogue and debate were encouraged to increase the level of commitment to the objectives that had been defined in common.

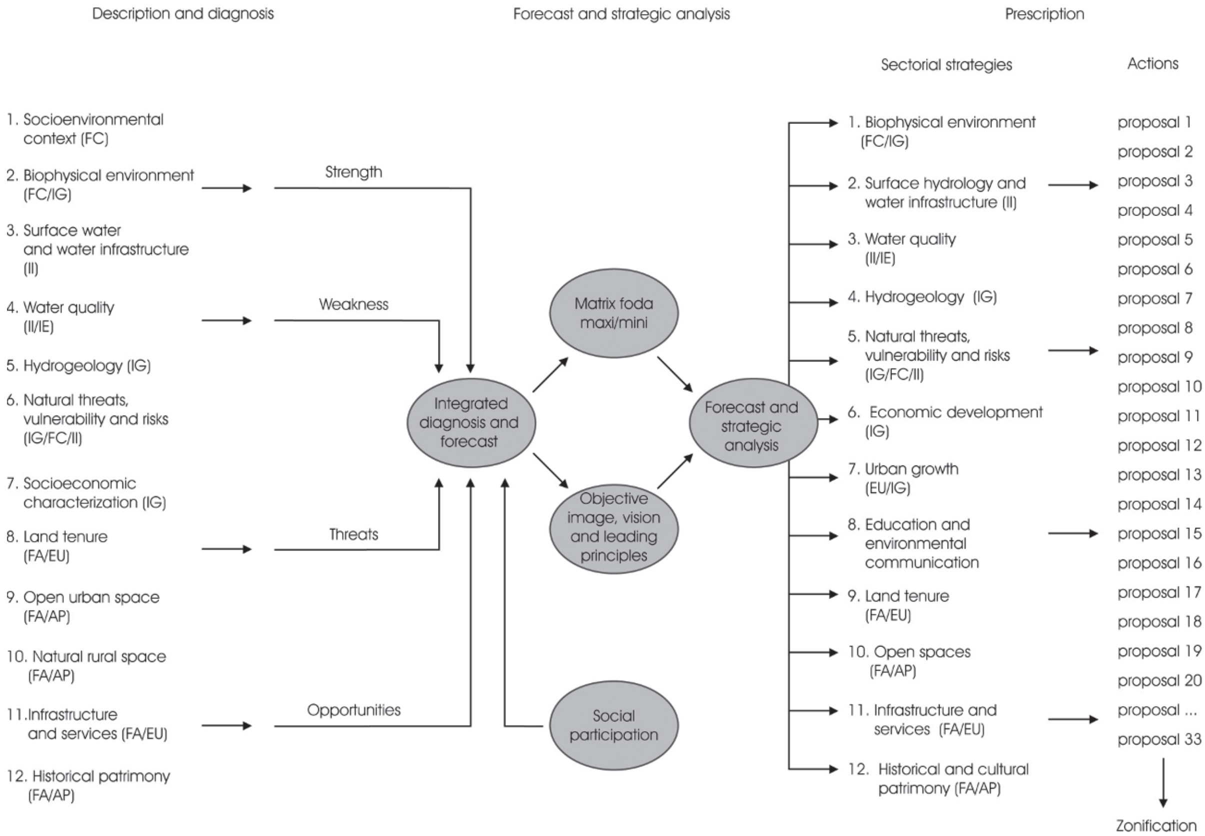
With time, because of the dynamics of the meetings, actors developed a shared language and abilities they did not previously possess (Johnson, 2003). This process was plagued by differences. Diversity was at the core of the working sessions, and it was only thus that common agreements were reached and consensual goals and lines of action were set.

The Magdalena River Master Plan has an innovative trait: the basic reference terms of the project became the first consensual document approved by all working groups, whereas previously basic reference terms had been set and imposed by the government and consulting groups. Instead, in this case, they were widely discussed by a Promoting Group composed of citizens, scientists, businessmen, NGOs, and private consultants who had been drafted in to help produce a preliminary proposal. This initial proposal was discussed in working meetings until a final version was agreed and incorporated into the Master Plan as a set of basic research components, reference terms, and expected outcomes. This process lasted approximately two months.

The first stage of integration involved making a description and diagnosis. A document was drafted with the problem description and diagnosis as seen by each discipline; this was very useful for assembling empirical evidence and systematizing information for each working team. In this way, 12 thematic descriptions were gathered, each respecting disciplinary boundaries in terms of theoretical, methodological, and technical approaches.

With these thematic descriptions, a first integration exercise was conducted, following the socio-environmental systems approach (Musters et al., 1998). In the integrated diagnosis, it was no longer important to look at specific issues in the basin, but to have instead an overview illustrating the interrelationship of different processes. This first integrated proposal was subjected to interdisciplinary scrutiny and was refined in a workshop involving researchers' critiques and modifications. It is also important to emphasize that

Figure 29.4: Integration stages. **Source:** Developed by the authors (2009).



in this process, the diagnoses were incorporated that had been conducted in the participative planning workshops. Thus, the method not only organized the experts' thematic descriptions; it also included the processes identified by the basin's inhabitants (figure 29.4).

The intermediate stage was an exercise in forecasting and strategic analysis. It included a trends scenario and a programmatic scenario, i.e., a target image of the Master Plan. With the target image it was possible to put forward the first proposal for a general intervention strategy in two workshops – the first with the interdisciplinary team and the second with the authorities from the *Ministry of Environment in Mexico City* (SMA) – in order to define the ensuing lines of action. This was the stage with most interdisciplinary work among the different teams, as it was essential to become familiar with the proposals and results put forward by other disciplines. Becoming acquainted with others' work was also useful to the groups when drafting their own proposals.

The last stage was prescriptive; it dealt with developing particular lines of action and situating them territorially. Spatial analysis was the dimension where all proposals were systematized, and their technical, legal, and social feasibility evaluated. In order to develop particular lines of action, each expert received a document with all the citizens' proposals linked to their field. The premise was to try to incorporate the greatest possible number of proposals as long as they were compatible with the target image, the technical diagnoses, and the results of the interdisciplinary zoning.

29.4 Results

The result following this working process was a strategic platform that integrated five strategies, 14 general objectives, 35 lines of action, and 254 projects. The richness of the projects resulted from the integration of proposals made by citizens, scientists, and government authorities.

The first strategy of an *Ecosystemic Management and Sustainable Local Development* included all proposals directed at the conservation of natural resources and at ordering economic activities on the land, such as farming, agriculture, and ecotourism services.

The second strategy of a *Comprehensive Management of the River and its Hydrological Basin* concentrated all actions intended to improve water quality. In the debates that took place, the use of models of groundwater flow can be highlighted, which broadened the scope of the area under study and included the zones of infiltration and the springs that feed the river. Another interesting proposal made by civil organizations with a view to avoiding the construction of marginal collectors was the use of eco-techniques and treatment plants to cleanse the river.

The third strategy of an *Urban-landscape Revaluation of the River* concentrated all the architecture and landscape projects in order to enhance the river-city relationship. One of the results of the project was identifying the opportunity to develop one of Latin America's largest linear parks linked to an urban river (nearly 13 km). This is a medium- and long-term goal which can set an important precedent for similar projects in the future.

The fourth strategy of a *Territorial Ordering for the Rescue of the Magdalena River* resulted from using various criteria such as water availability, topography, forest conservation, and economic activities, in order to have an orderly disposition of the land, resources, facilities, and services, following the prescriptions of the Master Plan. This strategy included managing irregular settlements, a problem that is not as pressing when compared to neighbouring basins, although it still calls for particular actions in order to contain the problem.

Originally, the basic reference terms included a section for identifying the instrumentation mechanisms that favoured the execution of the Plan. The integration team decided to group this section with other parts in order to present it as part of the strategy instead of as a purely technical element. In this way, the fifth strategy was developed.

The fifth strategy of a *New Governance to Help Implement and Monitor the Rescue of the River* included a system for certifying new projects. This system may prove an innovative and useful mechanism in order to guarantee the Plan's mid- and long-term continuity. Overall, the Master Plan's duration is five years. After this period, it needs to be revised and updated. However, the system of certification of new projects gives the Plan flexibility from the first year it comes into effect. Thus, new projects may be incorporated depending on budgetary constraints, changes in the environmental system, or the emergence of new social groups and their commitment to work on a local project.

Once the Plan is at its executive stage, it is imperative to implement certain specific indicators in order to measure its degree of progress and the impact on the system.

Given the duration of the project, fieldwork was undertaken during the first six months of the year, corresponding to the dry season. This bias in data collection provides an incomplete overview of the working of the hydrological system. Besides this lack of information other desirable aspects of fieldwork that were not essential were not undertaken owing to a lack of resources; they would be advisable in other and future projects. However, with these precedents, a research agenda was drafted in order to pursue fieldwork in the basin. Decision-making under this comprehensive river management approach will be more effective according to the quality and quantity of available information. It is not advisable for project leaders to follow a close collaboration scheme with authorities and officials who may be in competition with each other over some aspect of the area.

A recurrent critique of Master Plans is that they over-generalize and thus it is difficult to translate them into executive projects (Southern New Hampshire Planning Commission; 2002). Keeping this in mind, planners have made Master Plans more specific in order to identify critical zones and design proposals.

With this in mind, the authors believe that the range of projects –254 in total - is quite wide and may prove difficult to translate into action by stakeholders. Because of this, a selection of triggering projects was integrated into an *Immediate Action Plan* (IAP). The objective of this IAP was to maintain an integral outlook when starting to execute projects, organizing them according to strategic intervention areas.

The selection of trigger projects did not just incorporate the technical-academic viewpoint. In order to maintain basic consistency with the integration plans, levels of acceptance and viability as seen by citizens and government authorities were also accounted for.

In order to establish acceptance by citizens, the database of all civil proposals made in the participative planning workshops was revised. In some cases, similar proposals had been made in different workshops. Afterwards, the lists that had been distributed to the different scientific teams were revised in order to select those that were technically viable and matched the goals of sustainability in the basin. After these two controls, the projects that were technically viable and socially acceptable were discussed with the authorities. Some were ruled out given that their objectives were the same as other projects currently under way, whereas others were dismissed because of budgetary limitations. Following this selection process, from the vast range of 254 projects, 16 were selected to be implemented in the short run. They were closely related to the wider organizational structure of the overall project.

29.5 Conclusions

The rescue of urban rivers and the development of projects linked to water management both call for new planning strategies where scientific, civil, and government knowledge can be integrated, opening novel inter-sectoral communication channels, and seeking consensual agreements.

In this regard, civil participation is essential for making projects viable in the short, medium and long term. This does not mean validating scientific and technical rationalities socially. Instead, it means incorporating citizens in the processes of finding solutions to pressing social problems and implementing them. The emphasis shifts from participation to the active construction of shared responsibilities. This scheme of integration favours horizontal information flows, overcoming hierarchical and vertical trends in traditional planning. Making citizens co-responsible is a useful alternative in order to guarantee the continuity of projects beyond changes in the terms in office of governments.

The cornerstone for the development of the Magdalena River Master Plan was the inclusion of different viewpoints, types of knowledge, social representations, and interests in order to generate consensus and favour the river's rescue. The challenge for the integration team was forging an organizational logic capable of systematizing heterogeneous proposals and clearly establishing the strategy of the Master Plan.

Tactically, it is generally recommended that the Master Plan has a set of projects to be implemented in the short run. This set of projects must be shared and discussed, and it may constitute the best presentation card for the project, especially with civil society. If, on the contrary, projects are inadequately selected and results are deficient, citizens' trust and civil participation may be lost. If that occurs, it will be very difficult to implement a new rescue plan in the near future.

As well as civil co-responsibility, the integration team must prepare a flexible plan, with a logic open to constant feedback cycles. Plans must not be immutable. Their continuity depends to a great extent on their capacity for incorporating new empirical evidence (research agenda), the ongoing evaluation of results (system of indicators), and their capacity for incorporating new projects once changes in the socio-environmental system start to emerge (new project certification system).

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30 Assessment of a Water Utility Agency: A Multidisciplinary Approach

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30.1 Introduction[1]

This chapter describes the methodology for an action plan for solving the water supply problems of a city of around 400,000 inhabitants, with a semi-dry climate and a subterranean supply system. This plan was based on a diagnosis of the supply sources, the demand for drinking water, the operation of water treatment plants, and the commercial and accounting system, as well as the analysis of possible alternative supply sources for the city and its adjacent urban areas. The actions that have been proposed in this action plan are focused on increasing the supply of water, both in terms of quantity and quality, to meet the needs of the population and to operate the supply system more efficiently.

Providing a water service of quality that should be the mission of all water companies in Mexico in charge of water supply and treatment. But the drinking-water sector faces enormous obstacles: supply coverage must be extended, the rehabilitation of infrastructure has fallen behind, as has the institutional development of operational and commercial practices, as well as technical training, among other things. Therefore, an improvement of services to achieve an 'adequate' quality level of supply is difficult to attain in the short term, and there are many views about how it might be achieved.

There are few companies providing a good quality water service, with a sufficient volume, around the clock, and with a minimum delivery pressure of 1.5 bar. The common justifications for non-compliance have been: low prices, lack of support, non-payment by the users, etc.

Regardless of the quality characteristics to be applied to the water supply, the improvement process should be quantified, the procedures for measuring progress over time should be defined, and, if possible, the associated costs should be assessed. It is common to argue that water companies must improve, but specific aspects and a quantification of the improvements needed are seldom mentioned.

Generally speaking, a water supply operating agency will not be able to offer a quality service to the population if the following aspects are not complied with: an infrastructure that is capable of providing the amount of water needed by users, good quality water at the source that falls within the standards established for human consumption, and a continuous water supply at a minimum pressure that doesn't require users to build their own domestic storage and pumping systems.

When a poor quality service generates dissatisfaction among the population, this will translate into a reluctance to pay for the deficient service. To this one must add the poor collection capabilities of operating agencies, largely due to the fact that their commercial divisions do not have the appropriate mechanisms to facilitate payment by consumers; furthermore, there are no adequate price-defining mechanisms that allow recovery of the real cost of the service.

The low collection levels that result from administrative and technical problems and the very low prices for water supply services in several regions of the

1 Keywords: efficiency of operating agencies, water quality, water supply

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country generate financial deficits; i.e. the operational expenses are larger than the income generated through collection by the water supply service. This generates a situation where the economic resources are insufficient to adequately operate the systems and where the infrastructure deteriorates from day to day. This same situation prevents an adequate maintenance and solutions are often improvised in order to continue operating both the equipment and the systems. Operating under these conditions becomes more expensive, and electro-mechanical efficiency is far from optimal.

In the case of transport and distribution of water, it is difficult to know with any degree of certainty exactly what the volume of physical losses in cities may be. In many cases, there is no macro-measurement and as a consequence it is impossible to know precisely how much is being produced. As for the measurement of consumption, the other component of efficiency, the 'real' micro measurement levels are low. In the absence of statistics concerning leaks in networks and domestic facilities, it becomes impossible to know what the levels of deterioration in the distribution infrastructure are, and this is compounded by the lack of a transparent water register (Ochoa/Bourguett, 2001).

This problem has already a solution (at least, in logical terms): collection levels must be increased, commercial procedures must be made more efficient, and service must be improved through an increase in the number of hours of availability, the amount of water available, the pressure in the supply, and through ensuring treatment of 100 per cent of the water being supplied to the network. These are all aspects that are directly related to the technical operation of agencies. Finally, more convenient price rates should be established, based on the capacity for payment of the population served and on the actual cost of the service.

Taking all these factors into consideration, the goal of this chapter is to establish an information database based on an analysis of the procedures and on the operational status of an agency that may be considered as typical of several regions in Mexico.

30.2 Methodology and Diagnosis

30.2.1 Analysis of Demand and User Satisfaction

The first step in any diagnosis is to establish the water needs of the population. In the context of this study, the analysis was based on the consumption obtained from the billing data of the operating agency in charge of the system, and this was compared with a random sampling carried out for a week at 400 domestic taps from all over the urban area. The selected sample is considered to be representative of the total population (Montaño, 2002) (>100,000 inhabitants) and the only restriction established for selecting the taps was that they all had to have a water meter installed. If this was not the case, the nearest tap having a meter was selected in place of the one without it.

Shown below are the mean values obtained in the course of our random sampling of consumption: a) Domestic consumption (working-class and residential areas) of 109 l/person/day; and b) Commercial consumption of 382 l/tap/day. At every selected tap, the existing meter was exchanged for a new one having the characteristics shown (table 30.1) and provided with air ejection valves to avoid measuring errors due to service rationing.

Table 30.1: Models of water measuring. **Source:** By the Authors.

Brand:	Actaris	
Model:	TM II	
N designation flow:	1.50	m^3/h
DN:	15.00	Mm
Nominal pressure:	10.00	Bar
ΔP:	<1.00	Bar
Class:	B(H)	

The water meters that had already been installed in the field were classified by brand and model, in order to group them as a benchmark for the purpose of determining any errors of under- or over-measuring they might exhibit and which would necessarily have an effect on the measurements carried out by the operating agency. Both the under- and over-measurement in a domestic water meter are generally due to the following:

- a lack of preventive maintenance programmes;
- water quality characteristics: iron, calcium contents, etc.;
- associated problems such as sand in the water;
- rationing of the service;
- climate factors;
- faulty installation; and
- wrong choice of equipment.

Table 30.2: A projection of demand, production, and deficit under the conditions found in the study area. **Source**: INEGI (Statistic and Geography Institute) and CONAPO (National Population Council).

Year	Population (Projections)	Demand (l/s)			Production* (l/s)	Deficit (Considering 250 l/person)
		300 l/person/day (100% coverage)	250 l/person/day (100% coverage)	Increasing coverage		
2005	430 204	1 494	1 245	1 019	537	708 l/s
2006	433 047	1 504	1 253	1 040	537	
2007	435 895	1 514	1 261	1 075	537	
2008	438 750	1 523	1 270	1 111	537	
2009	441 628	1 533	1 278	1 147	537	
2010	444 528	1 544	1 286	1 183	537	
2012	450 421	1 564	1 303	1 257	537	
2014	456 459	1 585	1 321	1 333	537	
2016	462 619	1 606	1 339	1 411	537	
2018	468 854	1 628	1 357	1 491	537	
2020	475 109	1 650	1 375	1 572	537	
2030	504 533	1 752	1 460	1 790	537	923 l/s

* Mean production considering wells and springs

All of the above affect the equipment, which may then age prematurely, leading to a loss of precision in the measurement of consumption. It is important to evaluate this kind of error in order to determine the volume of water that is not being measured – due to a lack of precision in the water meters – and therefore is not being charged for. This would allow an estimate to be made of the reliability of the amounts being billed.

This case study assumed that water meter measurements were not reliable, given the poor quality of the water and the low levels of supply. This last factor was reflected in the fact that virtually all the population (94.5 per cent according to polling) received a discontinuous (rationed) service, with 60 per cent receiving water for no more than five hours a day. This situation has affected the proper functioning of water meters, resulting in public dissatisfaction.

When it came to the verification of water meters, only 19.5 per cent of them were correctly measuring consumption according to the NMX-CH-001/3-1993-SCFI standard, and almost the same percentage of meters were faulty. The rest of them exhibited measurement errors of between 6 per cent and 12 per cent; therefore, consumption measurement was deficient, resulting in unreliable billing.

Both consumption measurement and polling contributed to the diagnosis of the operating agency's problems. Nevertheless, in order to be able to estimate the supply required by the population, a volume of approximately 300 l/person/day was taken, in accordance with the procedures published by the National Water Commission (CONAGUA, 2004), which includes actual consumption plus 40 per cent (as per the data obtained from the same agency) in physical losses, i.e., water not accounted for in the whole process of transportation, treatment, and distribution.

An analysis of growth of supply was made for two scenarios: 1) assuming 100 per cent coverage exists; and 2) enlarging coverage up to 100 per cent. In the first case, mean supply was compared at both 250 l/person/day and 300 l/person/day (table 30.2).

From this projection, a 250 l/person/day supply generated a 1,245 l/s demand during the year of the study, a figure that was projected to grow to 1,460 l/s by the year 2030; that is 708 and 923 l/s above the actual production. An additional adverse factor was that concessions authorized by the National Water Commission allowed only for an additional 422 l/s of production, given the area's availability of water.

30.2.2 Analysis of Water Production

For water production, the operating agency had interconnected water wells in different subsystems, which were also fed by spring water. In the year during which the study was conducted, the mean production of water, taking into account wells and springs, attained 537 l/s as indicated in table 30.1, of which 465 l/s were produced solely by wells. Nonetheless, analysing extractions from those wells since the time when they began production, a maximum historical mean of 919 l/s was identified, meaning there was almost a 50 per cent decrease in production from the time at which they began operating.

This is not unusual, as a fall in production is one of the problems generally exhibited by water extraction wells. Among the factors causing this fall, the following can be mentioned: build-up of scale in the well casing, filter blockage, sand production, structural collapse of the well casing, and poor condition of the pumping equipment.

A good maintenance programme begins at the time a well is built, by recording and keeping records of its lithology, monitoring the quality of its water, and keeping track of its specific capacity. Inspection and maintenance programmes should be established, taking the individual characteristics of both the pump and the well into account, although the operational history of other wells in the area should also be considered. It is important to consider the operational characteristics of the well and the pump, as both may deteriorate to a point where rehabilitation becomes almost impossible. The experience indicates that if the specific capacity of a well experiences a 25 per cent reduction, it is time to begin rehabilitation. Not doing so significantly increases the maintenance costs.

The following may be used to evaluate a well's performance:

- static level;
- flow after a period of continuous pumping;
- dynamic level after a period of continuous pumping;
- specific capacity after a period of continuous pumping;
- amount of sand in water samples after a period of continuous pumping;
- total well depth;
- normal flow and number of hours of operation;
- level at wells in the same area; and
- well abatement caused by the operation of nearby wells.

In order to establish an analysis of the causes of falls in production at the wells, video recordings were made of the interior of these wells (figure 30.1). These videos showed that the well casings exhibited a significant build-up of scale, possible collapse, and production of sand and slime. In general, the casings were not regularly cleaned because of the risk of collapse and because of a lack of financial resources for replacing any parts that might be damaged during the disassembly of the equipment.

Apart from the condition of the wells, it is necessary to be aware of the conditions under which their pumping equipment operates. This can be done while at the same time evaluating their efficiency through the measurement of the following parameters:

- operational flow;
- pumping pressure;
- pumping levels;
- voltage;
- electrical current;
- power factor; and
- column friction losses.

These parameters allow the equipment's electro-mechanical efficiency to be determined (CONAGUA, 2003) as well as the causes of inefficient operation, so that actions can be proposed for replacement, performing maintenance, or rehabilitating the equipment, as the case may be. If this exercise is carried out periodically, preventive actions can be established, the use of resources, equipment, and personnel can be optimized, and the causes of low well performance and productivity can be diagnosed; furthermore, there can be feedback of information for the purpose of selecting and installing the electro-mechanical equipment.

Figure 30.1: Camera used to record the interior of water supply wells. **Source:** By the authors.

If machines work at below their nominal capacity, this leads to a low power penalty by CFE (*Federal Electrical Power Commission*), as the energy consumption is over-billed. If its capacity is exceeded, the equipment operates at a low electro-mechanical efficiency. Centrifugal pumps are designed to operate efficiently at a given water flow and speed, their optimal efficiency point. Operating the equipment outside this point generates additional stress on certain parts of the pump and this damages it. Efficiency in pumps extends their useful life and saves electrical power during their operation.

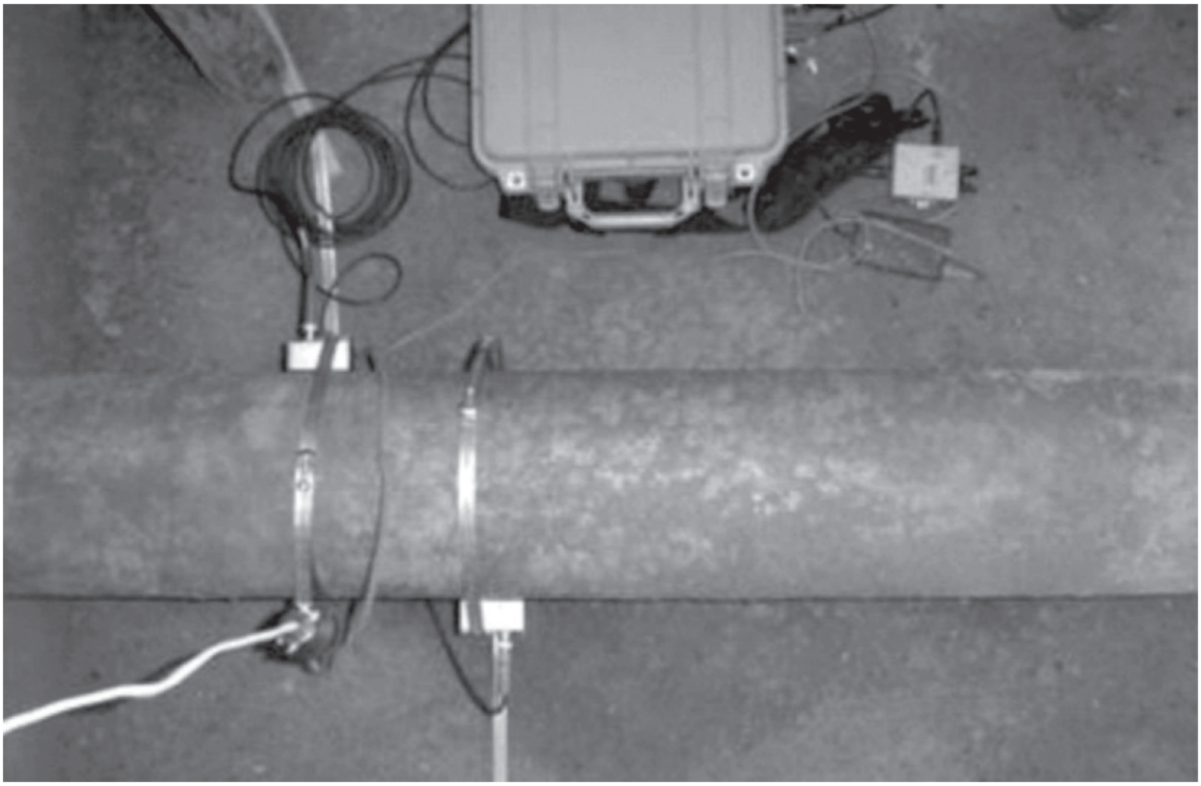
On the other hand, one of the most important parameters affecting the efficiency of the equipment is operational water flow. Low performance may be related to a lack of maintenance of the equipment and of the wells. This produces a build-up of scale in the grooved casing that obstructs the free circulation of the water bed, resulting in a reduction of the flow of the water that is being extracted. Wells are designed for a 5-year operation, after which they have to be rehabilitated.

The equipment and methods that were used in this study to determine electro-mechanical efficiencies are:

- The measurement of the water flow was carried out using transit time ultrasonic measurement devices (figure 31.2) that are placed at measurement stations complying with the specifications for minimum distances between the macro-measurement device and the special pieces of well equipment (Bourguett O. V et al., 2001).
- Pumping or discharge pressure of equipment was measured using a Metron pressure gauge having a +/-0.1 kg/cm^2 accuracy, connected as close as possible to the pump discharge point.
- For pumping levels, the dynamic level was determined using a HGE electric probe having a 1.0 metre scale. A 0.01 metre rounding was carried out using a 5-metre long flexible Trupper measuring tape.
- Voltage and amperes were measured using a YF-8020 YFE hook Voltmeter/Ammeter with an accuracy of: +/-0.1 Amperes (max. 600 A) and +/-1.0 Volts (max. 750 V).
- The power factor was taken from the Federal Electrical Power Commission's monthly bills.

At every pumping unit, three or four regular readings were taken of pressure, dynamic level, electrical tension, and electrical current during a 72-hour opera-

Figure 30.2: A transit time ultrasonic measuring device for measuring the flow at a water extraction supply well. **Source**: Authors' photo.



tional period at each well. The electro-mechanical efficiency was calculated using the procedure established in the National Water Commission's Guide (CONAGUA, 1993, 1993a, 2003a, 2004) and basic hydraulic equations (Streeter/Wylie, 1998; Giles et al., year). About 67 per cent of the equipment showed electro-mechanical efficiencies below those that are recommended for the replacement or repair of the equipment.

It was further observed that low water production was related to the deterioration of the extraction and distribution infrastructure. At some wells, the pumping equipment was replaced with equipment with a lower capacity, while the same machines were used that had been designed for other work conditions. Another common practice was 'tweaking' the equipment to extract less water, due to a decrease in a well's production. The interaction of all these factors contributed to low efficiencies in the pump-engine set, all of which resulted in extraction problems and high production costs.

30.2.3 Analysis of Operational Systems

Water distribution in several Mexican cities is adapted to the changing needs of the population, often without any study of the best operational conditions for ensuring efficient distribution of the water throughout the network. The situation deteriorates itself when a system has no reliable distribution network registry that allows its growth to be planned in an orderly fashion. This case study was no exception, and most transportation lines operated also as distribution lines, since reliable plans for transportation and distribution networks were lacking. Because of this, the pumping equipment had to face drastic changes in its working conditions. This was one reason why water was not treated for human use and consumption before it was pumped into the secondary network to reach the consumers.

A check was also made to determine whether the operating agency had a macro-measurement programme that allowed the water volume that was entering each system to be determined with precision. However, it was observed that the existing macro-measurement devices at the wells rapidly developed a build-up of scale due to the presence of scale-forming pollutants in the water. In fact, the installed measuring devices did not comply with the necessary minimum specifications for ensuring correct measurements, as they were positioned with no reference to the minimum distances required from any obstruction in the discharge train (Ochoa, 2001). One action carried out in this study was to install measurement stations at each well at locations that permitted reliable measurement of the flow.

30.2.4 Analysis of Water Treatment and Quality

Water quality is another important factor when considering the correct functioning of a supply system. In this study determination of water quality was undertaken in both the dry and rainy seasons, by taking regular samples at each well in the system. The sampling and analysis was carried out by personnel from the Laboratory for Water Treatment and Water Quality of the Mexican Institute for Water Technology, an entity certified by the *Mexican Certification Agency* (EMA). Sampling was carried out in accordance with the standard NOM-014-SSA1-19923 "Sanitary procedures for the sampling of water for human use and consumption in public and private water supply systems" and analysis was performed in accordance with the Amendment to Official Mexican Standard NOM-127-SSA1-1994, adopted in 2000, on environmental health, on water for human use and consumption, and on permissible quality and treatment limits for drinking water.

Results showed that the water extracted from the wells did not comply with the maximum limits allowed by NOM-127 for several parameters. This required an evaluation of the treatment plants to be able to determine the type of water that was supplied to the population. As the treatment plants must supply water that complies with NOM-127, all operating agencies that have treatment plants within their responsibility must check whether the use of reagents, of water in backwashing processes, and filtration runs are adequate for optimizing the cost of producing each cubic metre of water.

The operating agency under study had a potabilization plant with complete clarification of the water, and this plant was analysed for the following purposes:

- to carry out a diagnosis of the way treatment plants work and to make relevant recommendations for the purpose of improving their operation;
- to evaluate how each process of the treatment system works, including field sampling of the operational control variables. The evaluation included measuring the operational water flow at the point of entry to each plant, an analysis of the oxidation status of incoming polluting agents, contact times at each unit, hydraulic behaviour, and efficiencies in removing pollutants;
- to carry out water treatment tests on a laboratory scale to establish the theoretical efficiency of the process being used;
- to carry out treatment tests at a pilot scale to propose improvements in process efficiency;
- to prepare an operation and maintenance guide in accordance with the specific characteristics of each plant; and
- to determine the technical and economical feasibility of the improvement actions required by the systems to ensure their proper operation, including the possibility of automating the dosage of reagents.

The evaluated treatment plants showed serious operating problems in all processes, mainly due to:

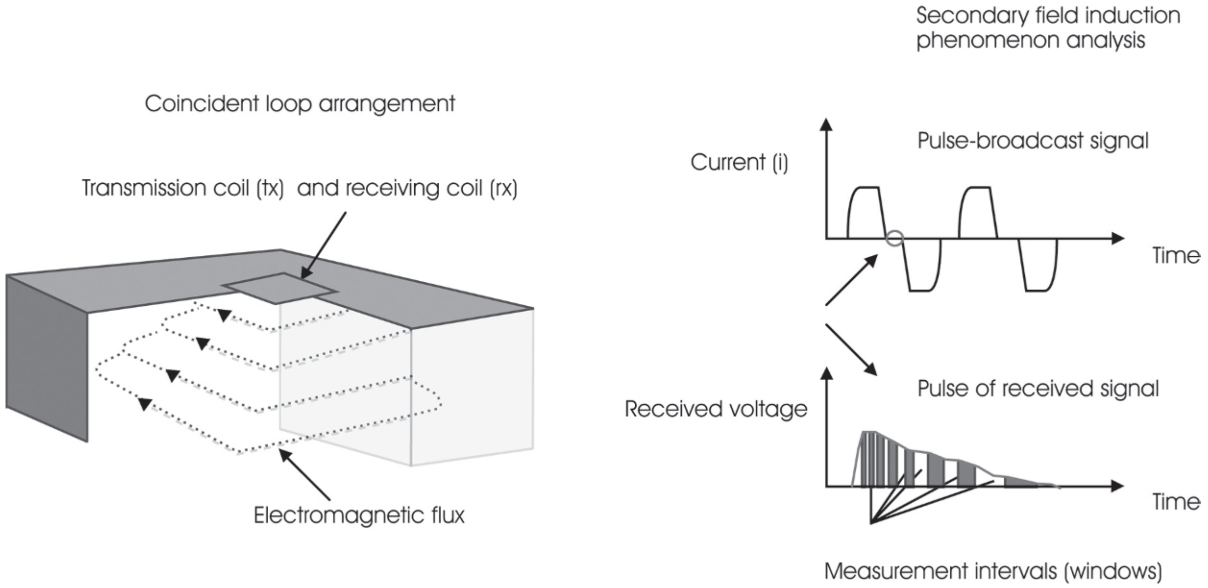
- a general lack of maintenance of equipment and units;
- absence of indispensable equipment for proper operation processes;
- a general deterioration of infrastructure and the clogging of filtering material;
- a lack of knowledge among the staff of the conditions under which each stage of the system must operate;
- a lack of updated procedures, laboratory materials, and chemical reagents at the laboratory;
- a lack of training of the laboratory staff; and
- drastic and frequent variations in the inlet flow at plants, with no automatic control of reagent dosage, among other things.

Treatment plants were evaluated following IMTA's manual (Martín et al., 1998) and other specialized publications (AWWA, 1990; CEPIS, 1992a; EPA, 1994) so that solutions could be proposed that involved technological changes and the rehabilitation of process units; the publications consulted were design guides taken from specialized bibliographies (AWWA-ASCE, 1998; CEPIS, 1992b; Montgomery, 1985).

30.2.5 Analysis of New Sources of Supply

After they had been rehabilitated, the operating wells did not supply the required production to cover the

Figure 30.3: Coincident loop arrangement. **Source**: Designed by the authors.



water deficit that the city and its adjacent urban areas were suffering. A total of 95 geophysical probes were carried out in the study area to identify probable perforation zones for new wells within the urban and adjacent areas. These probes were carried out using the *Time Domain Electromagnetic Transitory Method* (TDEM), one of the most modern geophysical techniques for prospecting groundwater, in order to calibrate the equipment and to offer technical and scientific support for interpreting the data measured.

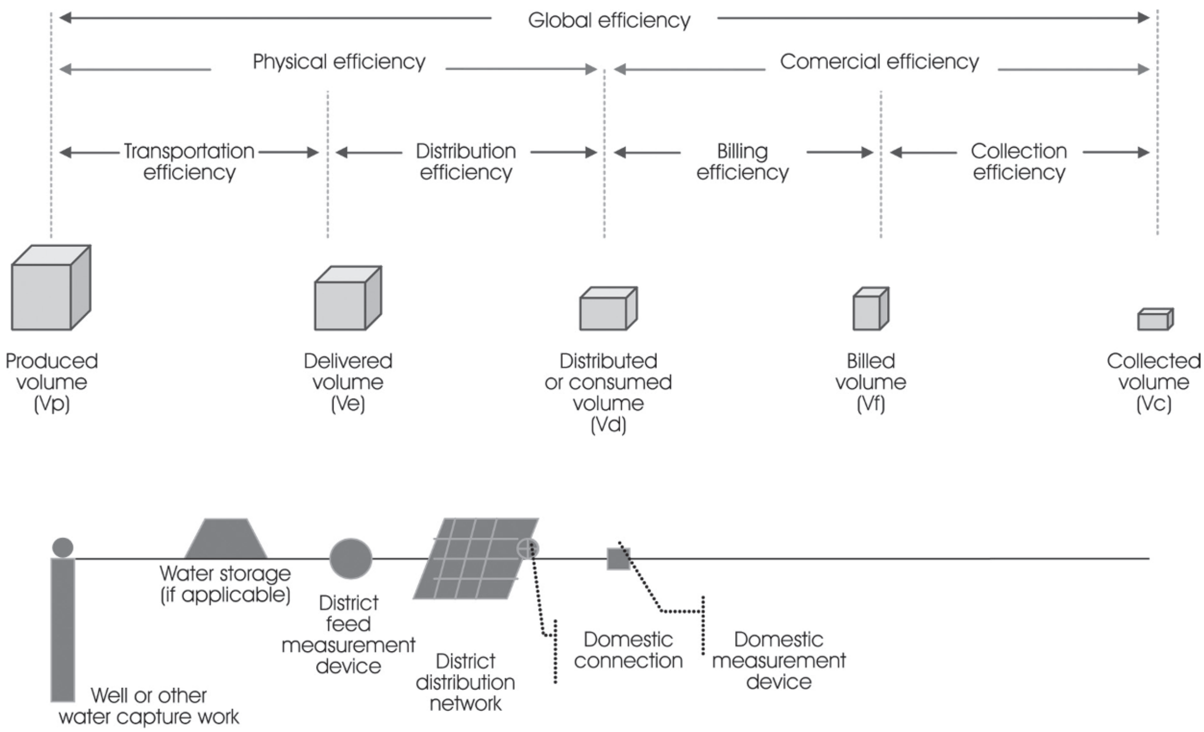
Through use of TDEM the study sought to show the distribution of groundwater in terms of homogeneity, based on a resistivity characterization (Spies et al., 1986; CONAGUA, 1993, 1994a; Temix S., 1993; Winglink, 2001). Due to its high vertical resolution, this technique allows a very realistic image of the underground conditions to be obtained. In parts of the sub-soil, it is possible to observe the heterogeneities (or anomalous areas) caused by the presence of geological structures, facies changes, and rock fractures, where the presence of water has an effect on the value measured, contributing to important changes in resistivity, the experimental field parameter that is being measured. TDEM uses a spiral or coil formed by a cable in the shape of a square, measuring either 150x150 metres (an area of 22,500 m^2) or 300x300 metres (an area of 90,000 m^2) in a arrangement called a 'coincident loop' (figure 30.3).

A series of tests were carried out using this arrangement, which consisted of introducing variations on parameters such as:

- transmission and reception circuit resistance tests;
- circulating the current intensity analysis;
- noise analysis and response of equipment under different gain rates;
- analysis of sub-soil signal penetration (depth of investigation);
- analysis of repeatability of the response measured by the equipment;
- signal build-up with means from 256, 512, 1024, and 2048 samples;
- record processing was carried out in the following stages for each probing, as follows:
  - transfer of records to the computer;
  - recorded curve editing for each gain rate, in order to obtain a final NV/AMP curve against time (decay curve);
  - conversion of decay curve to Apparent Resistivity against time,
  - calculation of stratified model,
  - calculation of softened model (Occam inversion);
- transfer of curves and generated models, integration of the database; and
- preparation of iso-resistivity plans and sections.

All stages of the above process were carried out in the laboratory, and field data was analysed on the same day it was recorded. GPS was used to track the measurement sites. The results permitted the conclusion that there are 3 areas in the study zone with the capability to extract 100 l/s, 300 l/s, and 350 l/s, respectively.

Figure 30.4: Diagram representing the different stages that allow the efficiency of an operating agency to be measured. **Source:** Designed by the authors.



30.2.6 Analysis of the Efficiency of the Operating Agency

One of the basic aspects of ensuring an operating agency is functioning well is its efficiency in correctly measuring what it produces, distributes, and collects (CONAGUA, 2003, 1997; figure 30.4).

As has recently been mentioned, the operating agency did not have adequate equipment to measure production efficiently. Global indicators that could have been compared with the national mean (CONAGUA, 2004) gave a better idea of how the system was operating during the study. Regarding the efficiency indicators, the coverage, supply, water not accounted for, and functioning micro-measuring devices, as well as the income per tap, the average income, and the income per sale were all low compared with the national mean. Thus, the number of employees for every thousand taps was very high, as were the unit production costs. The main reasons for the problems identified in this study for the operating agency were as follows: costs were much greater than income, price structure was inadequate, and collection rates were low.

Public opinion about the service received from the operating agency was determined through polls carried out at the sites where the measurements of consumption were also carried out. Twenty-two questions were drawn up in order to establish the users' level of satisfaction. The *closed question* format was selected for the poll questions, where the individual is asked to give an answer from multiple choices. The main goals of the polling focused on:

a) establishing the users' perception of the quality of the service provided by the operating agency through an indirect evaluation of the main parameters, such as the level of service, its continuity, its pressure, and the quality of water;
b) establishing the willingness of the users to pay;
c) obtaining information on how users would grade the service they receive; and
d) determining the users' willingness to accept an increase in the price they would pay for the services in exchange for an improvement in those services.

The results (table 30.3) showed that a high percentage of the population was either dissatisfied or indifferent, received poor attention, did not have enough water to satisfy their needs, received water only every few days and then only for a few hours, needed to build cisterns because the water did not get to their

Table 30.3: Result of the polls on the quality of service. **Source:** Authors' results.

Service quality	%
Dissatisfied or indifferent	55.5
Insufficient water supply	42.0
Water 1-3 days/week	87.5
Water 1-5 hours/day	59.0
Not enough pressure in the supply	85.0
Received unsatisfactory service from the operating agency	40.7

Taps with quality problems	%
Flavour	32.0
Odour	59.0
Colour	67.5
Cloudiness	57.2

dwellings with enough pressure to reach the rooftop tanks, and even then, they still had to deal with water quality problems. These polls were also useful for detecting taps that were not registered among the users. This allowed an estimate to be made that 6 per cent of the taps that had a meter were not recorded in the system; clandestine taps must be added to this figure to assess the total volume of the water that is neither billed nor paid. In conclusion, the operating agency had several options at its disposal for improvements, which, once implemented, would help to increase efficiency, thus allowing it to offer a better service to the public.

30.3 Results or Actions Proposed

Those actions that were proposed as a result of the study focused on attaining a production level that would be sufficient to meet the needs of the population with the quality that was required by the applicable standard, through a more orderly and efficient operation of the water supply system.

30.3.1 Covering the Production Deficits in the Short Term

30.3.1.1 Rehabilitation of Wells and Equipment

A rehabilitation of existing wells was recommended to enable them to reach their production capacity or at least approach it, in order to cover a part of the large supply deficit that was observed during the study period in the relevant urban area. The proposed rehabilitation consisted of chemically and pneumatically cleaning the wells' casings to remove the different minerals that have caused the low production. Once the cleaning was completed, it was recommended that equipment should be selected that was best for complying with the operational conditions of the system (having the same equipment for pumping directly to the distribution network, and avoiding the re-pumping of tanks).

The water quality of the aquifer requires that the wells receive frequent attention and that their maintenance is programmed for at least once a year. It was further proposed to improve the conditions of every pumping station, carrying out maintenance on discharge trains and protecting them from vandalism.

It was estimated that through these actions of rehabilitation the production of the wells could increase from an annual average of 466 l/s to approximately 775 l/s. When this difference is added to the reported annual average production of 71 l/s from springs, this would generate a supply equivalent to 846 l/s. With an existing coverage at the time the study was conducted of 65.45 per cent and a mean supply of 250 l/person/day in working-class homes and 300 l/person/day in residential homes, the deficit would be reduced by 21 per cent. Furthermore, there would be an electro-mechanical efficiency improvement so that less electricity would be required.

30.3.1.2 Sectioning and Interconnecting Transportation Networks

This recommendation derives from the substantive needs of the operating agency under study to improve the operation of its distribution network:

- The incorporation of new wells in the water distribution network and the resulting greater flow would necessarily produce changes in the network's method of operation.

- The need to treat the water extracted from the aquifer before distributing it would modify their operations, because transportation lines would be needed between the wells and the treatment plants and distribution lines between the latter and the final users; furthermore, new treatment plants would also be needed.

Therefore, it was proposed that the macro sectors should use the existing infrastructure; that is, transportation lines should be used within their capacity to lower the costs for new infrastructure. Reinforcements of the lines and/or the building of new ones were also proposed in order to derive the maximum benefit from the available infrastructure. Thus, the existing treatment plants would be fully used, regardless of the recommendation to build new ones, so as to increase coverage of treatment to 100 per cent in these macro sectors.

30.3.1.3 Purchase of Rights from the Agricultural Sector

The existing permits for water extraction from the aquifer studied were insufficient to ensure full coverage of the long-term needs of the constantly growing population. In a potential water market, a transfer of water, to be negotiated between one sector of economic activity and another, is proposed, by purchasing a transfer of water rights. In this case it was suggested that negotiations should be entered into with agricultural producers who use the irrigation units in the region.

An estimate of the volumes that could be transferred and of the cost for the operating agency of paying agricultural producers for these volumes of water was considered within 5 scenarios, each of them with different options. These scenarios were: 1) a five per cent saving through efficient water management; 2) irrigation techniques; 3) productive reconversion; 4) the sale of concession rights; and 5) exchange of residual water. The option that was seen as being socially more acceptable was the 'productive reconversion', which meant only substituting the cultivation of grain and cattle feed for the cultivation of vegetables. But these alternatives will not solve the serious problem of the scarcity of drinking water in the study area if the work needed to increase the system's physical efficiency is not carried out.

Water exchange with other users, primarily from agriculture, would allow a sustainable use of existing resources and improve the quality of the service. But this action requires extensive political and social efforts to avoid conflict with the agricultural producers.

30.3.2 Improving Water Quality

30.3.2.1 Rehabilitation of Treatment Plants

A first stage of rehabilitating treatment plants focused on filters, which would allow a substantial improvement in water quality. Thereafter, efforts can focus on rehabilitating all processes, and on the laboratory, in order to solve the problems and to have a direct effect on the efficiency and costs of treating water. It is also essential to train the personnel operating the plants, control the way they work, and implement a preventive maintenance programme for both equipment and infrastructure.

30.3.3 Improving Physical Efficiency

30.3.3.1 Replacement of One Per Cent of the Pipes Each Year

In any distribution network pipes usually last between 30 and 50 years, depending on several factors, such as quality of the material, building procedure, water quality, and soil type. But recent evidence has shown that a discontinuous or rationed service places pipes under additional stress, as the cycles of filling and emptying them appreciably reduce their useful lifespan, sometimes by a factor of 10, compared with their usual time span for providing service under optimal conditions.

As the network of the city under study has been operating for many years in a discontinuous way, it was assumed that it must have deteriorated quite badly. But it was not certain which areas were the most affected, since there are no statistics regarding leaks, nor did a network registry exist; the percentage of failures was also unknown. However, the volume of lost water was relatively high, especially when the service was rationed. Therefore it was recommended that a policy of renewing the network at a minimum rate of 1 per cent a year be implemented (estimating 100 years for complete replacement); this rate is justified because of budgetary constraints, but, with a change in prices, it would be desirable to have at least two per cent of the network replaced each year.

30.3.3.2 Replacement of One Per Cent of all Domestic Taps per Year

The usual lifespan of the domestic tap infrastructure is affected by local operation conditions. It was therefore recommended that taps be replaced at a rate of at least one per cent per year to reduce the likelihood of leaks and because of low efficiency. Replacements should start where infrastructure is the oldest or at those places with the greatest percentage of reported leaks.

30.3.4 Dividing the Network into Sectors

The difficulties in operating the system, due to a low water supply and the high cost of increasing it, are among the causes why the operating agency was forced to maintain a high physical efficiency. One way to facilitate a reduction of the losses and to control them is to divide the network into sectors, something that also facilitates an easier and systematic operation. Therefore, it was proposed to divide the network into sectors with a mean rate of 12,000 taps a year in order to attain a complete network within a few years (Mays, 2000).

30.3.5 Updating the Network Registry

One of the most relevant activities for the planning and maintenance of an efficient network operation is to have an updated network registry. This registry is also very important for detecting and eliminating leaks, for programming repairs, etc. The absence of a reliable registry is at the root of the difficulties of planning operational modifications, such as day-to-day operation, since some actions are performed following established routines, without any consideration of whether they represent the most efficient way of attaining their purpose. It was therefore recommended, as an essential activity, that the registry be updated, something that would impact on multiple actions to improve the performance of the agency.

30.3.6 Increasing Commercial and Financial Efficiency

30.3.6.1 Updating the Users' Registry, the Accounting System and the Price Rate System

The registry of users had not been updated for many years. The revision of this registry was carried out as a part of this study and it revealed that a reclassification of users was necessary, since there were 97 types of users, when less than 10 categories should suffice for effective control, allowing the introduction of a price rate structure more in line with actual consumption.

The indicators for physical, commercial, and global efficiency were above the national average. Nevertheless, it was recommended that special attention be paid to collections from residential homes and commercial and industrial users with consumption greater than 480 m^3 in a two-month period, as this was the range showing the lower collection efficiencies.

It was recommended that a new system be launched that would allow the commercial, treasury, payroll, and storage systems to be linked, so that the accounting records could be automated. This system allows the identification of cost units by type of operation, such as water services, drainage networks, maintenance, user services, and administration. It was also recommended that a physical inventory of fixed assets be carried out, in order to quantify and appraise such assets and to be able to justify the evident need to replace them (Weston/Copeland, 1992).

For the operating agency it was essential to increase price rates in order to obtain the necessary resources to operate and maintain its services in an efficient, sustainable way and to generate resources to expand, improve, and replace the infrastructure. The price rates had not been modified nor updated in many years. It was also suggested that the intensive programme for collecting overdue debt be continued, and a proposal was made to modify and update the price structure.

30.3.6.2 Purchase and Installation of Home Water Consumption Meters

When it came to the measurement of water consumption, it was recommended that a medium-term programme for replacing the 6,800 water meters be launched. This would raise the system to an acceptable level of quality. It was further recommended that an institutional training programme be launched, to ensure that the staff has standardized basic knowledge. This is important since home measurement is one of the best tools to administer demand, control consumption, and generate fair collections based on genuine consumption. Evidence shows that greater coverage results in lower consumption in those cases where service is already reasonably good. In this case, it becomes necessary to renew the water meters after the supply deficit is eliminated and the network's water quality problem is solved. The purchase and installation of water meters was proposed so that there would be 100 per cent home measurement coverage by the year 2011.

30.4 Conclusions

This study diagnosed an operating agency with problems that are similar to those encountered in other parts of Mexico. Each aspect of the system's operation was taken into account, as the main goal of the operating agency should be to efficiently supply an amount of water that is adequate for the population's needs, assuring its quality in terms of current standards. Therefore, technical, commercial, and financial aspects were examined. Results showed that the operating agency was not complying with its goals for many reasons, which could be summarized as follows:

- There was a scarcity of water supply in the area and the available water was of very poor quality; furthermore, it was not efficiently extracted and distributed. In general, the infrastructure required large investments to operate adequately, but the financial resources that were needed were non-existent. The operating system presented many opportunities for improving its administrative and financial aspects, including the fact that there were more personnel than needed, and that this personnel lacked training.
- The problem was a complex one, since there was a low rate of data collection that could not be increased without first improving the service; at the same time, there were no resources to carry this out.

The main reasons for these problems, which apply to many other operating agencies in Mexico, are that expenditure is significantly larger than income. There is also an inadequate price structure and a low rate of collection. These kinds of problems are common for many operating agencies, but without a full diagnosis of the way they operate, the specific problems of each operator cannot be identified.

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31 Water Pollution from Agriculture: Policy Challenges in a Case Study of Guanajuato

Rosario Pérez Espejo

31.1 Introduction[1, 2]

In Mexico, as in many other countries, agriculture is the main user of water, and its prime polluter. Nevertheless, the country lacks an agro-environmental policy aimed at reducing the negative environmental impacts of agriculture. In many parts of the world the agricultural sector is not environmentally regulated due to: 1) the consideration that agriculture is a prioritized and sensitive sector and thus it should be protected and subsidized; 2) theoretical problems posed by the design of instruments for the environmental control of non-point sources; 3) the bias in support of and the resource allocation in favour of large-scale farmers with political influence who have traditionally been reluctant to allow regulation. The goal of this chapter is to discuss important problems involved in the design of environmental policies for the control of water pollution, as well as to present the preliminary results of a research project undertaken in Irrigation District 011 in the state of Guanajuato. The objective of the project was to obtain information to design a set of agro-environmental instruments for the agricultural sector from a theoretical perspective.

The chapter is structured in two parts. In the first part water pollution is discussed from an economic perspective. Agriculture generates two types of discharges: point discharges that are observable and can be quantified, and non-point or diffuse discharges, which are not easily observed or measured, because of the high cost of measurement. There is a vast economic literature focused on the design of economic instruments for agriculture. Nevertheless, the so-called 'second-best' instruments – those that are inefficient from a neo-classical economic viewpoint – have not yet been replaced. Thus, the environmental management of agriculture aimed at improving water quality has been based on voluntary or persuasive measures which only casuistic and indirectly could improve water quality. Mexico has a set of federal laws aimed at controlling water pollution. However, only two generic standards (NOM-001-SEMARNAT-1996 and NOM-002-SEMARNAT-1997) address the improvement of water quality. They apply to users that generate point discharges and use federal waters and land as receptors. In the agricultural sector, these standards only concern intensive farming units, especially pig farms and dairy farms. Two proposals for economic environmental instruments are noted in this chapter: a tax on pesticide use and the 'decoupling' of electricity tariffs for agricultural pumping.

In the second part of the chapter, the preliminary results of a study of Irrigation District 011 in the state of Guanajuato are presented. In this Irrigation District there is great pressure on water supply and quality. Irrigation District 011 illustrates many characteristics of contemporary Mexican agriculture: the fragmentation of lands, leasing, low levels of education, and ageing and unsustainable agricultural practices. A total of 73 percent of all water is used for low-value crops such as corn, sorghum, and wheat. Water quality analyses showed that according to national drinking water standards, the maximum limits were only exceeded by heptachlor epoxide, lindane, and methoxychlor; these pesticides are of restricted use in Mexico. Triazines and carbamates, for which there are no set standards, were also present at some points in the sample. The presence of compounds found at sampled sites shows that they were used at a certain time in the past, and they persist in drains and channels. The sampling was conducted at a time when no agrochemicals were in use. The predominant technology utilized in the area of study relates to the 'green revolution', and uses the classical inputs. Although these technologies were introduced over forty years ago, farmers still have insufficient training in using them properly.

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2 Keywords: agriculture, water pollution, public policy

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The objective of this study of the state of Guanajuato is to generate information that allows economic instruments to be simulated and also to detect economic, political, and institutional capacities for generating, expanding and/or reinforcing voluntary initiatives that link public persuasion with expert technical assistance.

The public policy vacuum in Mexico is not accidental; there are theoretical problems in the design of such policies, as well as political and institutional obstacles to the implementation of agro-environmental control measures.

International organizations such as the *Food and Agriculture Organization of the United Nations* (FAO, 2006) and the *Organization for Economic Co-operation and Development* (OECD, 1998) have clearly stated that agriculture is the most important cause of water deterioration. For example, the *US Environmental Protection Agency* (USEPA, 2000) claimed that agriculture was the cause of the worsening conditions in 72 per cent of the rivers and 58 per cent of the lakes; pesticides were found in 26 per cent of the rivers; nutrient run-off was found in 40 per cent of the lakes and 37 per cent of the rivers; organic material was found in 40 per cent of the rivers and lakes.

In Mexico, the potential estimate of land suitable for agricultural use is 30 million hectares (m.ha). However, only 23 m. ha are sown, and between 18 and 20 m. ha are harvested; livestock uses up to 110 m. ha. Overall, agricultural activities use 65 per cent of the national territory (CONAGUA, 2005). In terms of water, the National Water Commission claims that agriculture uses 76 per cent of the extracted water – both surface water and groundwater - whereas livestock uses 2 per cent (CONAGUA, 2005).

The *National Water Commission* (CONAGUA) is in charge of monitoring water quality in Mexico; it has systematically analysed the main water resources in Mexico since 1973. Until the year 2001, information provided by CONAGUA regarding water quality was based on the Water Quality Index. In 2001, it demonstrated that 74 per cent of water resources showed some degree of contamination, in one per cent toxic substances were found, and only 26 per cent was of an acceptable quality (CONAGUA, 2004).

Since 2002 information on water quality has been based in two parameters (table 31.1): *biochemical oxygen demand* (BOD) and *chemical oxygen demand* (COD). This methodological change does not allow comparisons over long periods of time and neither is it possible to know if changes reported by monitoring stations are due to a real improvement in water quality or if they are merely due to changes in the measurement methodology.

Table 31.1: Percentage distribution of monitoring stations for surface water quality according to category (BOD, COD, and TSS, 2006). **Source:** Statistics of Water (SEMARNAT-CONAGUA, 2007).

Quality	**BOD**	**COD**	**TSS**
Excellent	40.4	19.6	45.3
Good quality	25.3	18.9	33.0
Acceptable	17.6	23.8	14.0
Polluted and strongly polluted	23.0	37.8	7.9

Legend: BOD: *Biochemical Oxygen Demand*; COD: *Chemical Oxygen Demand*; TSS: *Total Suspended Solids*

The National Water Commission does not generate information on the impact of agriculture on water quality; however, it does recognize that some branches of agriculture such as intensive farming, pig farming, and dairy herds are among the most highly polluting industrial activities, generating 1,630 *million tons* (m.t) of organic material per annum (m.t/year). The only industries that produce more waste than agriculture are the sugar cane industry with 1,750 m.t/year and the petroleum industry with 1,186 m.t/year (CONAGUA, 2004).

31.2 Objective

The goal of this chapter is to discuss the problems involved in the design of agro-environmental policies for the control of water pollution and to present the preliminary results of an economic research project undertaken in Irrigation District 011 in the state of Guanajuato. The objective of the project was to obtain the information required to design a set of agro-environmental instruments for the agricultural sector from a theoretical perspective.

The chapter is in two main sections. In the first section, the theoretical aspects that are linked to the design of economic policies for the control of water pollution generated by agricultural non-point discharges are analysed, and Mexican policies on water quality are discussed. The second section presents the methodological tool used in this chapter and preliminary descriptive results obtained so far for this case study.

31.3 Theoretical Aspects

31.3.1 Water Pollution from an Economic Perspective

Environmental pollution is one of the clearest examples of an external economy or of an 'externality'. The work *The Economics of Welfare* (1920) by A. C. Pigou is considered the starting point for the analysis of external economies (or diseconomies). Decades afterwards, the publications of the economists Arrow (1950), Meade (1952), Scitovsky (1954), Coase (1961), Baumol and Oates (1969), to cite some of the most influential, made major contributions to the development of this theme.

Pollution as an externality, understood as the damage imposed by a productive activity on third parties – irrespective of whether they are individuals or enterprises (Bohm, 1997) – which requires compensation, has important connotations for economic theory as it suggests a failure of the market. The costs of the damage are not included in the accounts of the party causing them, but instead they are assumed by a third party. It is often said that these kinds of damages (for example air and water pollution, loss of biodiversity, extinction of species) 'have no market', or that there are no prices to indicate the value of the services or goods damaged.

With regard to the ways in which these damages can be 'internalized' by responsible parties, there are two main streams in conventional theory. The first supports state intervention through a series of measures that constitute what is best known as environmental policy. The second, which is marginal because it is largely impractical, is known as the 'Coase solution' or 'Coase theorem'. It asserts that conflicts generated by environmental problems, especially pollution, should be overcome through negotiation by the parties involved, and it suggests that there should be no damage compensation or external intervention.

Environmental policy has two main approaches and an alternative political proposal that is not based on the principles of economic theory. The first approach is direct, and is also known as regulatory or 'command and control'; it sets norms and standards that seek to implement technologies, licences, and prohibitions in order to control pollution. The second approach is that of market-based economic instruments for environmental protection such as taxes, subsidies, charges, grants, tradable permits, and the creation of new markets, including restrictions and assignment of property rights (Turner et al., 1994).

Although economic research has been successful in designing economic instruments, most of the world's environmental policy has the regulatory approach as its basis. This means the application of standards, given the reluctance by productive sectors to be environmentally regulated through taxes. The alternative proposal that does not stem from principles of economic theory is that of voluntary initiatives, which is primarily used in agriculture.

31.3.2 Non-point Source (NPS) Pollution in Agriculture and Agricultural Contaminants

Water pollution is due to natural or anthropogenic factors. Water resources (streams, rivers, lakes, and estuaries) receive and store waste and harmful substances from different sources. When the single source of pollution is identifiable and thus somebody can be held responsible for discharges, they are referred to as *point source (PS) discharges*; when it is impossible to identify either, they are called diffuse or *non-point source (NPS)* discharges.

Non-point source discharges include run-off from: a) deforestation; b) agricultural activities (fertilizers, agrochemicals, manure, soil erosion, and fattening farms); c) mining and petrol production; d) urban discharges (industrial and commercial effluents, public sewage, mowing); e) highway run-off, and f) building and construction (Spulberg/Sabbaghi, 1998). Another important source of non-point pollution is the erosion of virgin lands.

According to various international organizations (OECD, 1998, 2000a, 2000b; USDA, ARS, NAL, 2004; FAO, 2006), agricultural activities and changes in land use are the most important processes producing non-point source discharges. Among the many reasons that explain why farmers make use of practices that heavily pollute water, these are worthy of note:

1. Because farmers act 'rationally', they maximize benefits when they use a higher number of inputs compared with those who do not affect the resources of a population. In the absence of regulations and sanctions for polluting, the costs of the environment's assimilation capacities are zero, and the economic damage imposed on others as a result of pollution is not part of their accounts. If external marginal costs – costs the society pays – were added to the marginal private costs, the equilibrium point in the application of polluting inputs would be obtained with less quantity of inputs.

2. When it comes to inappropriate agricultural practices, fertilizers and pesticides are used excessively, often through lack of knowledge of how to use them correctly (Susmita et al., 2000). Also, intensive agricultural farms are enormous and have a high density of animals, making them environmentally hazardous (Innes, 2000). If the damage they cause has no costs, farmers will continue with such practices until the benefits diminish.
3. Generally, producers are not aware of the environmental damages their productive processes cause, and so they are not willing to voluntarily participate in shared-cost projects to overcome pollution (Spulberg/Sabbaghi, 1998). Sometimes producers are indeed aware of the environmental damages caused by their activities; however, their political influence is such that they can dissuade governments from imposing agro-environmental regulations (Shortle/Abler, 2001).

Water pollution by the agricultural sector is also a result of ineffective government intervention; governments promote policies with subsidized incentives for agricultural producers as a result of lobbying from large-scale producers and also because agriculture is seldom considered as a socially necessary activity. These subsidies have been decisive for the over-use of inputs and for water pollution, and in Mexico for the process of deforestation.

No agreement exists on what should be regulated, how regulations should proceed, and who should be involved in regulating discharges from non-point sources (Shortle/Abler, 2001). In addition, many researchers agree that there is no convincing understanding of the level of environmental control that farmers should reach, nor are there any easy steps to reach it (Maguette, 2000).

Agricultural activities, characterized by the abuse of fertilizers and pesticides, and intensive farming with its critical levels of manure generation are significant sources of point and non-point pollution. In some countries, *Concentrated Animal Feeding Operations* (CAFOs) are considered as a point source (USEPA, 2000). Nevertheless, spillage accidents in storage units, storms of unusual severity, and run-off from the use of manure-based nutrients in agriculture are considered non-point sources of water pollution.

31.3.2.1 Agricultural Contaminants

The results of water pollution from agriculture include nutrients, pesticides, sediments, minerals, and pathogens (Shortle/Abler, 2001).

1. *Nutrients*: especially nitrogen, phosphorus, and potassium applied to crops via chemical fertilizers and manure. Nutrients can pollute water resources by run-off, filtration, lixiviation, and atmospheric deposition.
2. *Pesticides*: dissolved in water or trapped in eroded particles, they can evaporate in the air or lixiviate. They can kill fish and other species, as well as causing damage to the predators and consumers of fish in the food chain, through bioaccumulation. They can annihilate plants and insects because they are food for birds and other species, and this puts human health and the ecosystem at risk; they are one of the possible causes of carcinoma.[3]
3. *Sediments and turbidity*: cultivation activities exhaust ground cover and erode soils, shedding particles that eventually reach the water. These sediments obstruct irrigation channels and drainage, increasing the risk of flooding and the costs of water treatment for other uses; they can also destroy aquatic life as they free phosphorus and other contaminants.
4. *Minerals*: minerals from traces of fertilizers, other agrochemicals, and livestock foodstuffs incorporate themselves in water bodies through the same mechanisms as nutrients and sediments. Increasing quantities of toxic minerals such as selenium, boron, copper, zinc, and lead threaten human health, damage aquatic life, and diminish recreational opportunities.
5. *Pathogens*: bacteria pollution, the main cause of damage to estuaries and the second most common cause in rivers (USEPA, 2000), has its origin in the inadequate treatment of human and agricultural waste.[4]

31.3.3 Non-point Pollution in Economic Theory

The specific problems of non-point pollution in the agricultural sector have stimulated the development of a theoretical stream known as the 'theory of non-

3 The chronic effects of pesticides on human health are not conclusive (Shortle/Abler, 2001).

4 In Mexico, half of the rural localities of up to 14,999 inhabitants – where 35 per cent of the national population resides - lack sewage and wastewater treatment systems (Special Concurrent Programme for Rural Development 2007–2012 / Programa Especial Concurrente para el Desarrollo Rural 2007–2012, Mexico, Gobierno de los Estados Unidos Mexicanos, Comisión Intersecretarial para el Desarrollo Sustentable).

point sources of pollution' (non-point discharges). Of the numerous specialists who have contributed to this topic, only some of the most important contributions will be reviewed.

31.3.3.1 Incentives and Standards

An article by Griffin and Bromley (1982) is often cited as the pioneer approach. It introduced the concept of '*non-point production function*' (NPPF) to directly measure agricultural polluting emissions that cannot be observed. Non-point production functions relate the production options (use of inputs) to estimated emissions based on hydrological and statistical models.

Non-point production function (NPPF) for the i^{th} farm is expressed as follows:

$$\mathbf{r_i(x_i, \alpha_I)}$$

where:

- r_i are non-point emissions or NPPF,
- x_i is the vector ($1 \times m$) of production options and pollution control (inputs),
- α_I represents the physical characteristics of the place (soil, topography).

Unlike point emissions that can be observed without error (form a pipe or chimney), the *non-point production function* (NPPF) represents a *proxy* estimator of non-observable non-point discharges. After setting a target for a body of water, estimations are based on environmental concentrations, which are the sum of point and non-point emissions, on prevailing natural levels of pollution ζ, and on the characteristics and parameters of the basin ψ.

$$\boldsymbol{a = a(r_1, ..., r_n, e_1, ..., e_s, \zeta, \psi)}$$
$$\boldsymbol{(\partial a/\partial r_i \geq 0 \ \forall_i, \partial a/\partial e_k \geq 0 \ \forall_k)}$$

where:

- r_i are non-point emissions for the i^{th} farm,
- e_k are point emissions for the k^{th} source,
- ζ indicates prevailing natural levels of pollution in the basin,
- ψ are the characteristics and parameters of the basin,

$$(\delta a/\delta r_i \geq 0 \ \forall \ i, \delta a/\delta e_k \geq 0 \ \forall \ k)$$

Following on from these deterministic relations and applying the principles of optimization, the authors made four types of economically efficient environmental instruments for non-point agricultural discharges: 1) an incentive based on input (or product) monitoring, for example a tax on fertilizers; 2) a standard system for estimated run-off, for example a norm regarding the estimated loss of soil; 3) a subsidy (or charge) to agricultural practices, for example a nutrient tax, and 4) a standard system of management practices, for example the use of zero-tillage agriculture.

The underlying – and unrealistic – assumptions of the model are: a) the regulator is aware of the benefits for the agriculturists of modifying their management practices, i.e., there are no problems regarding information, and b) run-off can be determined without error only by observing management practices.

31.3.3.2 Incentives for Management Practices

Following on from the basic model, in 1986 Shortle and Dunn developed a new model that includes two different premises: a) non-point emissions and the processes of transport and fate are stochastic and unobservable, and b) given imperfect information about these relations, the observation of inputs in the farm's non-point production function (NPPF) is no longer a substitute for measuring emissions without errors.

Shortle and Dunn examine four instruments and conclude that – without considering transaction costs – the most efficient measure to reduce non-point pollution is an incentive for management practices. The authors recognize that none of the strategies that are analysed are optimal or of a '*first-best*' type, and furthermore they warn that environmental measures that incorporate economic principles tend to be politically unacceptable.

31.3.3.3 Environmental Taxes

In 1998, Kathleen Segerson published an article that modified the commonly-used approach called 'best management practice' and its incentives. According to Segerson, direct regulations and estimated run-off taxes are inefficient and impractical for controlling non-point discharges. Instead, she proposes shifting the focus from individual units of analysis to the pollution of a body of water through a variable tax which varies according to concentrations of pollutants. She suggests a minimum and random monitoring strategy allowing the producers to select the productive technologies and treatment that are most suited to them.

31.3.3.4 Direct Incentives and 'Team' Participation Approaches

Eirik Romstad (2003) also criticizes non-point discharge policies that seek to modify observable practices (fertilization, manure application, agricultural conservation) linked to run-off in farms. The author states that a change in the quantity of nitrogen (N) fertilizers applied only accounts for 30 per cent of N in the run-off and that the real issue is the social cost of the instruments for reducing the remaining 70 per cent.

Romstad proposes a sophisticated model of direct incentives for 'team' participation by producers who discharge into the same water source. The authorities may put forward two alternatives: 1) standards that will definitely reduce their benefits, or 2) a favourable team contract in relation to option 1) if the team reaches the target emissions level, but which is unfavourable if the target is not met.

Romstad's hypothesis is that farmers will only choose option 2) if they all believe that the environmental target is reachable by the team. In addition, the authorities may add extra incentives: a) if the 'team' exceeds the target, all agents in the team receive a payment; b) agents are given the option to self-report if the agent believes the target will not be met and if this is the fault of this agent. Any agent that self-reports pays a fine that is smaller than the fine that is levied if the target is not met.

31.3.3.5 Trading

Some authors suggest that when point sources are allowed to reach target emission levels by buying off reductions from non-point sources, pollution control is achieved at a lower cost (Ribaudo/Caswell, 1999). This type of trading requires two preconditions: 1) that point and non-point sources contribute significant and *known* amounts of the pollutant they seek to reduce, and 2) that marginal costs of reducing non-point discharges are lower than those of reducing point discharges. This exchange requires a very high level of compromise from the authorities in terms of administrative costs and also acquiring the basic information in order to make trading happen.

Nevertheless, trading emissions on a one-to-one basis can prove extremely difficult given the heterogeneity and natural randomness of diffuse discharges as well as the obstacles posed by its obligatory observance (Horan et al., 2002).

31.3.3.6 Flexible Incentives

Flexible incentives (FIs) are environmental management tools that set environmental targets but give producers the freedom to choose their own ways of attaining them. The design of flexible incentives involves four central premises (Batie/Ervine, 1999): 1) flexible incentives are a means to an end and not an end in themselves, their success depending on setting clear environmental targets; 2) flexible incentives are not a panacea and need to be adjusted to local social, economic, and environmental conditions; 3) flexible incentives have high transaction costs and thus require institutional reforms, and 4) implementing FIs presupposes a high level of human capabilities from both the producers and the authorities.

Flexible incentives include a broad range of voluntary and compulsive instruments such as: charges, subsidies (soft credits, tax reductions or deposit-refund systems), government payments tied to environmental compliance, creation of markets (emissions trading and eco-labelling), 'peer pressure' ('moral persuasion'), education and technical assistance, and awards (green certificates and performance standards to allow for a choice of technologies).

31.3.3.7 Voluntary Initiatives

Because of the theoretical, political, and institutional difficulties associated with the design and administration of environmental policies for agriculture, the authorities have opted for a voluntary compliance approach which combines public persuasion with technical assistance towards attaining the adoption of control measures.

The voluntary measures cover the following programmes: 1) education, 2) research and development (use of sustainable agricultural technologies, biotechnology, development of resistant plant varieties, use of vegetation buffers, etc.), 3) green payments and subsidies (for example, subsidies to reduce nitrogen use), and 4) soil conservation (recommended practices and management for avoiding soil erosion).

These programmes may or may not lead to changes in the behaviour of producers, although criteria for their application usually depend on political circumstances.

31.3.4 Public Policy for Agricultural Non-point Discharges in Mexico

Most of the economic instruments previously mentioned, both those stemming from economic theory and those relating to voluntary incentives, are very rare in Mexican agricultural and environmental policies. Water pollution is controlled through two generic standards on wastewater discharges. In agriculture, these standards only apply to intensive livestock farms, and exclude diffuse discharges.[5]

Programmes such as the 'Ecological Procampo' and the 'Programme for Hydrological Environmental Services' were not originally designed to improve water quality in water resources, although they may indirectly influence it. The 'Ecological Procampo', which is jointly managed by the *Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food* (SAGARPA) and the *Ministry of Environment and Natural Resources* (SEMARNAT), offers subsidies for agricultural practices and crop cultivation that halt the processes of soil erosion. The programme covers over 20,000 hectares (less than 1.0 per cent of the total national cultivated areas) with payments that range between $963.00 and $1,1160.00 Mexican pesos per hectare (OECD, 2003).

For the conservation of water sources, in 2003 SEMARNAT launched the 'Programme of Hydrological Environmental Services'. Its objective is to protect the recharge capacity of aquifers and to reduce sediments, and it allocates payments of $300.00 Mexican pesos to each hectare of forest to that effect.[6]

Given this legal vacuum in environmental regulations, two agro-environmental policy proposals are worth mentioning: a tax on pesticide use (Muñoz/Ávila, 2005) and a 'decoupling' of the electricity tariffs for agricultural pumping (Avila et al., 2005). It is worth mentioning that in Mexico pesticides that are banned at national and international level are still used and even subsidized. Excessive use of pesticides and fertilizers, together with the negative consequences for human health and water quality, has been well documented in many parts of the world (Susmita et al., 2007).

Given the toxicity of pesticides,[7] the proposal is to: 1) remove VAT exemptions on all pesticides regardless of their level of toxicity; 2) reduce taxes in proportion to an optimal zero toxicity, i.e., 5, 10 and 15 per cent, and 3) tax the most toxic pesticides at 10 per cent while exempting others.

The proposal for a 'decoupling' of the electricity tariff proposes giving farmers the same money they currently receive as agricultural electricity tariff subsidies in cash.[8] In Mexico, water for agricultural use is free of charge and electricity for pumping is subsidized even for farmers who have no official permits, and as a consequence 88 per cent of the most important aquifers Mexico are over-exploited.

The overall proposal contains five different scenarios for using subsidies efficiently: 1) subsidize over-exploited aquifers only (30 per cent of its users); 2) give an average subsidy to all users, whether they have official permits or not; 3) subsidize according to historical averages of water and energy consumption; 4) subsidize only users who have an official permit, and 5) provide farmers with a payment for each cultivated hectare (as with PROCAMPO), even if they do not have an official permit.

31.4 Case Study

31.4.1 The Area of the Study

The study[9] that is the basis of the preliminary results reported in this chapter was undertaken in Irrigation District 011 (DR 011) in Guanajuato. This state was selected because of its agricultural importance, brought about by the pressures of urban, agricultural and industrial growth on water resources, especially as most of the state is located in the Lerma river basin, one of the most polluted in the country.

The Lerma and its tributaries receive diffuse discharges from agriculture (fertilizers, pesticides and other kinds of agrochemicals), point discharges from important industrial and population centres (for example, the industrial corridor of Celaya, a PEMEX refinery , a CFE electricity plant in Salamanca), intensive pig and dairy agricultural areas (in Pénjamo, Abasolo and Irapuato), and medium-sized cities such as Cortazar, Acámbaro, Salvatierra, and Abasolo, as well

5 NOM-001-SEMARNAT-1996 is a standard law that establishes the maximum permitted limits of pollutants in wastewater discharges into national waters. NOM-002-SEMARNAT is a standard law that establishes the maximum permitted limits of pollutants in wastewater discharges into municipal sewers.

6 See at: <http://www.mexicoforestal.gob.mx/nota.php?id=136> (February 2009; Muñoz et al., 2008).

7 According to the World Health Organization, pesticide sales in Mexico consist of: 17 per cent extremely toxic pesticides, 44 per cent highly toxic, 21 per cent moderately toxic, and 18 per cent slightly toxic (Muñoz/Ávila, 2005).

8 This subsidy is up to 700 million US dollars per annum (Ávila et al., 2009).

9 PAPIIT project (IN 305107) "Agro-environmental policies for water pollution control".

Figure 31.1: Location of the state of Guanajuato, Mexico. **Source:** Developed by author, based on INEGI (2009), "Información geográfica".

as numerous smaller towns. The state of Guanajuato has two irrigation districts: La Begoña with nearly 15,000 hectares, and Irrigation District 011-High Lerma River with 115,000 hectares; the latter accounts for an important share of the value of agricultural production in the state.

31.4.2 Guanajuato: Agricultural Importance and Water Use

The state of Guanajuato is located in the central part of Mexico (figure 31.1), and its territorial area represents less than 2 per cent of national territory. Approximately 80 per cent of the state is located in the Lerma-Chapala Basin, where several rivers converge; the most important is the river Lerma, which supplies the city of Guadalajara and five of the seven most important lakes in the country (CONAGUA, 2004).

The average water availability per inhabitant per annum in the state of Guanajuato has fallen from 2,800 litres in 1950 to over 800 litres by the end of the 1990s. The number of exploited wells – most are unauthorized or clandestine – increased from 2,000 to 16,000 in the second half of the 20th century at the same time as groundwater levels decreased by two metres every year on average (Sandoval/Almeida, 2006).

Agriculture uses 87 per cent of extracted water and it is one of its main sources of pollution together with the Salamanca refinery, the CFE electric plant, and various industries that fail to comply with Official Mexican Standard 001 regarding wastewater discharges.

Based on monitoring using *Biochemical Oxygen Demand* (BOD), the Lerma-Santiago-Pacific region is among those with the lowest average of monitoring stations with excellent water quality (30.1 per cent), whereas it has one of the highest averages of strongly polluted water (4.2 per cent) and polluted water (19.2 per cent; see table 31.2).

Monitoring using *Chemical Oxygen Demand* (COD) presents a similar situation: the Lerma-Santiago-Pacific region displays a high percentage of monitoring stations with water classified as highly polluted (14.4 per cent), and a low percentage of stations with excellent water quality (10.0 per cent).

Based on criteria such as the water availability per capita, the degree of pollution, the over-exploitation of wells, and the pressure over water, the Lerma-Santiago-Pacific region in general and the state of Guana-

Table 31.2: Per cent of monitoring stations of surface water resources by administrative region using the BOD5 category, 2003. **Source:** CONAGUA, Sanitation, and Water Quality Department (2005).

Administrative Region	Excellent	Good	Acceptable	Polluted	Strongly polluted
I. Baja California Peninsula	43.7	12.5	18.8	25.0	0.0
II. North-west	80.0	20.0	0.0	0.0	0.0
III. North Pacific	70.	15.0	15.0	0.0	0.0
IV. Balsas	28.2	15.4	23.1	28.2	5.1
V. South Pacific	n/a	n/a	n/a	n/a	n/a
VI. Bravo River	69.2	7.7	23.1	0.0	0.0
VII. Central North Basins	90.0	10.0	0.0	0.0	0.0
VIII. Lerma-Santiago-Pacific	30.1	20.5	26.0	19.2	4.2
IX. North Gulf	66.6	16.7	14.3	0.0	2.4
X. Central Gulf	62.2	5.4	2.7	18.9	10.8
XI. South Frontier	71.9	6.3	3.1	15.6	3.1
XII. Yucatan Peninsula	91.7	8.3	0.0	0.0	0.0
XIII. Valley of Mexico	4.0	12.9	20.0	40.0	32.0
TOTAL	51.8	12.9	15.7	14.3	5.3

juato in particular display a high level of vulnerability that threatens inhabitants' health and the ecosystem and in the future might even jeopardize economic activities in the region.

In the state of Guanajuato, the primary sector generates seven per cent of *Gross Domestic Product* (GDP).[10] The value of agricultural production in Guanajuato occupies the ninth place at national level, and livestock the fifth; nevertheless, given its size, it ranks 22 at the national level. Agricultural activities use almost 60 per cent of the land, of which agriculture uses 34 per cent (SAGARPA, 2009).

The importance of irrigation in Guanajuato cannot be over-stressed; of the 1,050,000 hectares that were cultivated in 2007, about 500,000 (48 per cent) were irrigated. This surface area comes third in importance in Mexico after Sinaloa (810,000 hectares) and Sonora (513,000 hectares). In Guanajuato, 85 per cent of the value of production was obtained from half of the cultivated surface area.

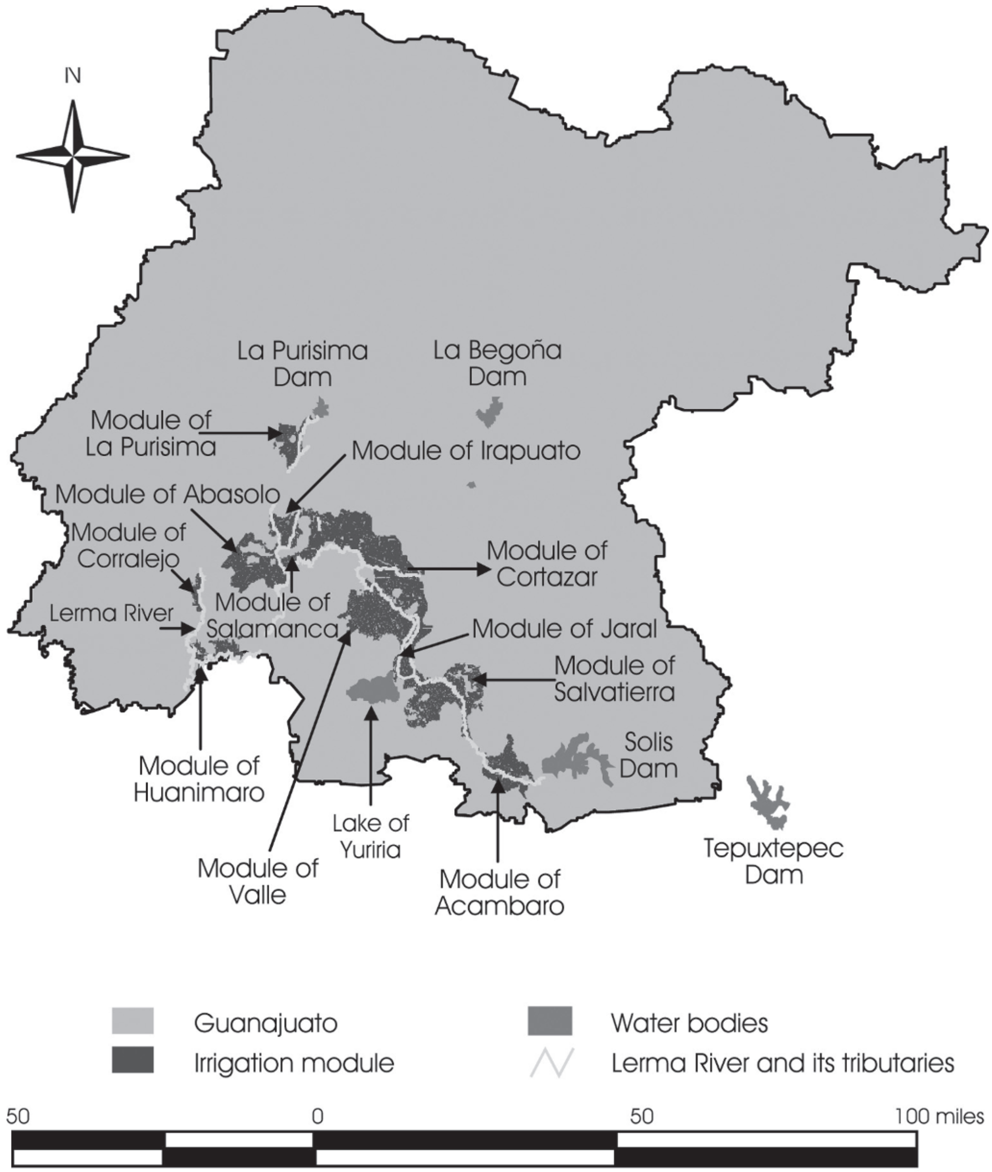
10 The *National Institute for Statistics* (INEGI) reported for the year 2004 a GDP of $4,128 million pesos for primary activities, in which the share of forestry and fishing is insignificant.

31.4.3 Irrigation District 011

Irrigation District 011 (IR 011; figure 31.1) is one of the most important in the country; it has over 25,500 users registered in an area of 115,000 hectares that are subdivided into 11 irrigation modules. In order to undertake field work, the user registry of IR 011 was obtained from the National Water Commission in the Arc View GIS 3.2 format. From this, the seven modules closest to the Lerma River were selected, representing 72 per cent of the total surface area of IR 011, and 69 per cent of total users (table 31.3).

The areas of farmers' land were normalized using natural logarithms {irrigation surface (1+1n)}, histograms were constructed and lands were classified in three categories according to their average (P) and standard deviations (S) as: i) large (P+3S), ii) medium (P+2S), and iii) small; ranges varied slightly between modules. The size of the sample was determined according to the human and financial resources of the project. Following on from this, a representative sample was calculated according to size, crop type (information gathered directly at the modules as it was not available from the central offices of the National Water Commission), and irrigation type for the agricultural cycles autumn-winter 2007-2008 and spring-summer 2008 in the modules of Cortazar, Valle de Santiago, Jaral del Progreso, Huanímaro, Acámbaro, Salamanca, and Salvatierra.

Figure 31.2: Irrigation District 011 (IR 011). **Source:** CONAGUA and INGEI (2008).



The collected data are being analysed with SPSS software, using regression analysis. At a subsequent stage, functions for production value and costs will be estimated using SAS and/or Econometric View, in order to simulate the effects of economic incentives in the profitability of the production unit.

The field work was undertaken between June and December 2008; 145 survey questionnaires were conducted and managers and personnel at the Guanajuato State Water Commission, of the Agricultural Trust Fund (*Fidecomisos Instituidos en Relación con la Agricultura*: FIRA), and of the State Ministry for Agricultural Development were interviewed.

Alongside the administration of the survey, 62 water samples were taken from sewage systems in the seven modules selected within the irrigation district ID011, in order to determine the presence of chemical components of pesticides. The analysis of the samples was undertaken at the laboratory of the Programme of Environmental Chemical Engineering and of Chemical Engineering at the Faculty of Chemistry (National Autonomous University of Mexico).

Table 31.3: Irrigation district 011 High Lerma River. Registered users and area by module and total. **Source**: CONAGUA Agency, state of Guanajuato (2008).

Modules	Area (ha)	% share of the District	% share of the total 7 modules	Users (#s)	% share of the District	% share of the total 7 modules	ha/user
District Total	115,536	100.0		25,543	100.0		5.0
Total 7 modules [(a)]	82,672	71.6	100.0	17,583	68.8	100.0	5.0
Abasolo	17,978	15.6		5,498	21.5		3.3
Acámbaro	8,551	7.4	10.34	1,738	6.8	9.9	4.9
Corralejo	1,557	1.3		275	1.1		5.7
Cortazar	18,331	15.9	22.17	3,045	11.9	17.3	6.0
Huanímaro	3,803	3.3	4.60	834	3.3	4.7	4.6
Irapuato	8,331	7.2		1,268	5.0		6.6
Jaral	6,714	5.8	8.12	1,390	5.4	7.9	4.8
La Purísima	4,998	4.3		1,018	4.0		4.9
Salamanca	15,915	13.8	19.25	2,702	10.6	15.4	5.9
Salvatierra	16,072	13.9	19.44	5,523	21.6	31.4	2.9
Valle	13,287	11.5	16.07	2,252	8.8	12.8	5.9

(a) Acámbaro, Cortazar, Huanímaro, Jaral, Salamanca, Salvatierra and Valle de Santiago

31.5 Results

1. Except that 97 per cent of the sample was male and so does not adequately represent the overwhelmingly female nature of Mexican agriculture, this study of ID 011 illustrates many aspects of contemporary Mexican agriculture such as:
   a) fragmentation of the land: average land per producer was 2.9 hectares in Salvatierra and 6.6 in Irapuato;
   b) leasing: unofficial estimates range up to approximately 60 per cent of the total area of ID 011;
   c) low levels of education: 10 per cent of producers have no schooling, 38 per cent have unfinished primary instruction, and 17 per cent did not complete high school;
   d) ageing process: the average age is 53 and half of the producers that have no schooling are over 59; and
   e) widespread absence of environmentally sustainable agricultural practices.

2. In relation to the production systems and agricultural practices it was found that:
   a) During the *autumn–winter* (AW) cycle, grains occupied 80 per cent of the farmed lands, required 73 per cent of the water, and generated 72 per cent of the production value. In turn, vegetables used 17 per cent of the land area, 9 per cent of the water, and generated 15 per cent of the production value. During the *spring–summer* (SS) cycle, the soil-water-production value relationship is even more favourable for vegetables, given that they used 11 per cent of the land, needed 5 per cent of the water, and generated 28 per cent of the production value (table 31.4).
   b) In the SS cycle, around 51 per cent of the producers irrigated by gravity and 37 per cent used wells. In the AW cycle, 41 per cent irrigated by gravity and 35 per cent with wells.
   c) In the SS cycle, 74 per cent of producers reported the use of improved seeds, fertilizers, and agrochemicals that could be insecticides, herbicides, or fungicides. This proportion was 56 per cent in the AW cycle. Minimal fractions of farming land (less than one per cent overall) were left fallow in both the SS and AW cycles. During the AW cycle, only 8 per cent of farmed land received compost as fertilizer, mainly corn, wheat, sorghum, and barley; in the SS cycle, this was 9.2 per cent.
   d) Biological plague control practices are used in the AW cycle in 6.7 per cent of cultivated lands

Table 31.4: Cultivated land, production value, and water use. **Source:** Research data, survey, based on the PAPIIT Project (IN 305107).

Autumn-Winter Cycle 2007-2008						
Crop	Cultivated land area		Production value		Water use	
	ha	%	thousand $	%	thousand m^3/ha	%
Grains*	1,508	79.6	33,133	72.0	242,198	73.8
Vegetables**	323	17.0	7,180	15.6	29,105	8.9
Others	65	3.4	5,693	12.4	57,119	17.3
Total	1,896	100.0	46,006	100.0	328,422	100.0
Spring-Summer Cycle 2008						
Crop	Cultivated land area		Production value		Water use	
	ha	%	thousand $	%	thousand m^3/ha	%
Grains*	1,719	81	31,326	70.6	575,324	85.7
Vegetables**	235	11.1	12,327	27.8	34,029	5.1
Alfalfa	157	7.4	468	1.1	40,154	6.0
Other	11	0.5	5,693	0.5	5,693	3.2
Total	2,122	100.0	44,346	100.0	671,242	100.0

and in 5.7 per cent during the SS cycle. During the AW cycle, the percentage of land according to crop type where biological plague control practices were applied was as follows: garlic (20 per cent), barley (2.9 per cent), and corn (8.5 per cent). During the SS cycle, the percentage was: garlic and broccoli (100 per cent), corn (5.8 per cent), and sorghum (6.7 per cent).

e) Around 25 per cent of producers – especially medium and large producers – use different soil conservation practices: minimum tillage, zero tillage, conservation tillage, and no-till or direct farming. These practices are not used by small producers as they lack the machinery and are not organized.

f) The majority of the producers throw agrochemical packages and empty containers straight into the trash without any special treatment (25 per cent), or they burn them (38 per cent); only 9 per cent take them to a special deposit.[11] Also, 25 per cent of interviewees declared having had health problems linked to the use of agrochemicals (hospitalization, nausea, dizziness, vomiting, and headache).

g) Irrigation District 011 is one of the main consumers of atrazine[12] (116.5 tons); within it the Cortazar module used 22.5 tons. Estimates of the lixiviation index using the Pesticide Leaching Potential (PLP) model provided high values for Salvatierra, moderate values for the Valle de Santiago, Cortazar, and Salamanca, and low values for Acámbaro, Jaral del Progreso, and Huanímaro (Hansen et al., PAPIIT Project IN305107).

h) The water quality analyses showed that with the exception of heptachlor epoxide – *organochlorinated pesticides* (OCPs) that have limits set by the standard for drinking water – limits were not exceeded. However, pesticides of restricted use in Mexico such as lindane and methoxychlor were found. Some other compounds such as carbamates and triazines were found in some samples; so far, there are no norms that set limits for their concentrations (Bernal, 2008).

i) The presence of certain compounds found in the sampled sites shows that they were used in the past and that they persist in drains and channels, even if at the time of sampling agro-

11 As part of a special programme called 'Clean Countryside' promoted by AMIFAC (*Mexican Association of Phytosanitary Industry*, in Spanish: *Asociación Mexicana de la Industria Fitosanitaria*).

12 Herbicide used for corn and sorghum; among the most dangerous pollutants according to Directive 76/464 of the European Union on pollutants of aquatic environments.

chemicals were not used. Also, there are certain compounds that are widely used but there is no standard methodology for their detection, making it hard to determine whether lack of detection was due to their absence or to not having adequate and reliable analytical tools for determining their presence (Bernal, 2008).

j) The technologies that were used in the area are of a 'green revolution' type, with its classical use of inputs such as: water for irrigation, hybrid seeds, and chemical fertilizers and agrochemicals, the latter supplied by transnational enterprises. Even though over forty years have passed since the introduction of these technologies, farmers still lack proper training in using them adequately. According to the survey, only 6 per cent of the producers had taken any form of training course on pesticides, weed control, the use of agrochemicals, or pest control.

31.6 Conclusions

1. The establishment of environmental policy measures to tackle agricultural water pollution faces many theoretical, social, and political problems that make this process very challenging. For this reason, the control of diffuse discharges in agriculture is largely based on voluntary programmes.
2. The Mexican agro-environmental policy is based on two generic standards for wastewater discharges that only apply to farms practising intensive agriculture. There are two proposals for agro-environmental instruments: a tax on pesticides and the 'decoupling' of electricity costs.
3. Given their internal organization and their links to government institutions, the irrigation districts – and particularly their modules – are the places where agro-environmental policies can be implemented, especially voluntary training programmes in sustainable agricultural practices and input use.
4. The authorities in charge of each module recognize that there are problems of misuse and abuse of all types of agrochemicals. Nevertheless, with the exception of the modules of the Valle de Santiago and Jaral del Progreso, where no-till farming is promoted, there was no interest in advancing sustainable agricultural practices at the modules.
5. In general, water use is rudimentary, by gravity. Only large-scale producers linked to vegetable exports use drip irrigation and practise sustainable management of inputs that complies with the demands of importing countries.

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32 Urban Water Management: From a Vicious Circle to Public Participation, Self-sufficiency and Sustainability

Nicolás Pineda Pablos and Alejandro Salazar Adams

32.1 Introduction[1]

Our advancement in knowledge is influenced by the reality that surrounds us. Our principal, though not exclusive, interest is in understanding the problems and phenomena that surround us and in finding solutions to them or the most appropriate ways of living with them. Water is not only an object of study in itself, but also an element of nature to which we can relate our goal of survival as a society, as well as increasing our level and quality of life. Also, the nature of water is dominated by the problem of scarcity. This resource limitation is significantly worse in particular regions where water is scarce, such as the arid and desert areas of northern Mexico and the south-western United States; the potential for increased climatic variability makes the situation more urgent. On the other hand, relative water scarcity is increased through population increase and through the concentration of population in urban nuclei that not only continually demand more water but also require appropriate institutions to efficiently manage the resource, as well as to contribute to the quality of life, including social and environmental sustainability. We consider institutions to be important in the relationship between human society, nature, and water management for this purpose (Ostrom, 2007).

By institutions we mean the combination of rules, procedures, and uses/customs that limit the behaviour of actors in a specific issue or field. In this sense, institutions determine the behaviours that people and social groups adopt when using water in their everyday lives or for agricultural and industrial purposes. The institutional framework for water management in urban centres is relevant to the quality of service and the quality of life of the population. It is also important for the conservation of hydrological resources as well as the sustainability of the environment and natural resources. Various factors determine the quantity of water consumed per capita and the volume of wastewater produced. These may include decentralization, degree of autonomy, citizen participation, designation of authority and responsibilities, and self-management, such as the service charge and the implementation of market structures. This puts into perspective the rules and components of the institutional arrangement of urban water management in Mexico, and allows us to reflect upon the actual form in which the service is provided. In general, it is suggested that urban water management has passed through stages of centralization and lack of participation, transfer to state governments, regionalization, and also the movement towards commercial and municipal providers of potable water. This chapter reflects on the demographic, environmental, and climatic challenges which cities will face during the next decade, and presents some possible research topics.

32.2 Citizen Participation and Public Debate

One line of research that is critical to the study of urban water management is citizen participation and the involvement citizens should have in strategic decisions. This is principally in respect of the construction of infrastructure within the context of the transition and democratic consolidation of Mexico.

In the analysis of social actors in projects and public works relating to the hydrological infrastructure, the theory of public policy considers that an actor is the individual or group, formal or informal, who attempts to influence a decision or public policy (Cahn, 1995: 201). It is important to distinguish between governmental and social actors. The first are incorporated in the formal structure of the public apparatus in any of its realms or levels and are those that pro-

1 Keywords: Potable water, urban management of water, institutional arrangements.

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mote, decide, and carry out public policy. The second originate from civil society and may be groups or individuals that attempt to influence, drive, or veto decisions and public policy. Social participation occurs when the decision-making process is not restricted to governmental actors alone, but where social actors are also involved. In a closed process only governmental functionaries participate, while in an open political arena a wide set of social actors are involved. This chapter argues that the degree of social participation greatly depends on the level of democratization in the political system. In this way, where more social participation and deliberation occurs, the level of democratization within the formulation of public policy is greater.

The capacity of the actors to influence and determine public policy is determined by four elements: a) the authority or power which they exert, b) the political resources which they control, c) their understanding of the problem, and d) their capacity for organization or social mobilization (March/Olsen, 1995: 92). Formal *authority or power* is provided by rules that are in force and by the political system, which signals who has the authority over resources and actions, and who is excluded from it. The authority of governmental actors requires legitimacy and that of the social actors requires autonomy. The legitimacy and autonomy of the actors are constant issues of controversy and discussion in democratic political processes.

The *resources* held by actors are not only human, financial, material, and technical, but they also include information, the time available, and personal or institutional attributes (such as charisma or leadership). The analysis of an actor's participation within the political arena then implies a review of available resources, such as asymmetries and differences between actors.

The third element is the *specific knowledge* possessed by an actor regarding an issue or problem, which they look to influence. Control over a theme comes from education, research, training, and experience. Institutions incorporate knowledge into their traditions and rules and have educational systems, archives, and libraries. The value of specific knowledge depends on the changing political agenda, the ruling beliefs, and the competence of groups with knowledge and alternative experience. In that case, the capacity generated by the knowledge is not absolute, but rather contingent and relative.

The fourth element is the *organizational capacity* that allows for the effective utilization of formal rights and authority, of resources, and of knowledge. Without organizational ability, the other abilities are lost. Organizational capacity can be eroded due to problems of coordination, control, logistics, scheduling, distribution, mobilization of effort, division of labour, specialization, motivation, planning, and the everyday tasks of filling roles, running a budget, and collective expectation. By means of organizational capacity, attention is concentrated on the aims and goals through which various activities are coordinated. When they are compatible, they may involve those who should combine themselves and utilize resources efficiently.

On the other hand, actors define themselves by their relationship to the issue, policy, or project in question. Schematically, in their most elemental form, they can adopt three positions: in favour, against, or intermediary. Actors in favour are those who, in general terms, support the policy as it is proposed and push for its advancement. Those who are against it propose different policies or alternatives and look to either prevent its development, or make drastic and fundamental changes. Intermediaries are those who assume an impartial position, or look to reconcile or press for negotiation between the sides. According to Sabatier's diagram (1993: 17), actors gather in advocacy and oppositional coalitions. Each coalition is a network that establishes explicit or tacit cooperative linkages within itself. The intermediaries may be higher authorities, media, or social groups who are more interested in maintaining political stability than in addressing the issue itself.

These coalitions act and exercise their influence in a specific setting. Often, the events surrounding the setting, unrelated to the theme or policy under discussion, determine the decisions or political actions. Sabatier (1993: 16) distinguishes between two categories of influence for the setting, the structural and the temporary. Determinants of the structural category include the characteristics of the natural resources, the culture and value structure, and the institutional and constitutional structures. Within the temporary category are the socio-economic conditions, the changes in the governing coalition, or events in other fields or spaces of political activity.

The actors interact in the political arena via public debate. There are a variety of theories and perspectives regarding the elements, the dynamic, and the processes of public debate. Reich (1988) suggests that there are two paradigms of how governmental decisions are made: maximization of net benefits and mediation between interested groups.

In the *focus on the maximization of net benefits* there is no unique debate. A closed set of actors, almost always governmental, make the decision based on technical studies, and thus determine which piece of work or project will result in the greatest social benefit. To do this: a) necessary information is obtained; b) alternatives are analysed, including the consequences of each option, and c) the alternative that provides the greatest net and social benefit is chosen (Reich, 1988: 131). This basically includes technical studies or research produced by the governmental office of analysts and advisers. In this case the social benefit is not defined by directly asking the public, but rather by the interpretation of that interest on the part of those who govern, whether it may be via proposals that they collect during their electoral campaign or via a mandate that they received in their election. This type of decision-making considers that once the governing party assumes their role, their function is to make decisions, without consulting with the citizenry for each decision. In the case of Mexico, the focus of public decision-making was that which prevailed during the authoritarian regimes of the hegemonic party or the state during the second half of the 20th century. However, it is worth mentioning that besides formal technical studies in these projects, personal interests, clientele relationships, and acts of corruption were often mixed in, thus creating the notorious consolidation of wealth among participating functionaries.

The *focus of mediation between interested groups*, for its part, considers that the role of the leader is to reconcile and even, when possible, to accommodate the diverse set of demands that are made by interested groups. In this case the leader serves as a referee or intermediary in the process of negotiation and social discussion. Their function is to be accessible and maintain themselves open to all demands without necessarily taking a stance, and also to make sure that the general interest prevails (Reich, 1988: 129). The decision is considered good when divergent demands are combined and reconciled and social peace is maintained. This decision-making process, where the leader plays the role of a mediator, can resemble judicial proceedings. The central challenge is to ensure the participation of all relevant interests, and that no particular group is excluded. Also, it is more likely that interests with better resources or better mobilizing capacity will end up dominating the issue. On the other hand, it is difficult for the leader to be impartial and reconciliatory, as key affected groups are often not invited to participate in the negotiations. Also, decision-making does not occur at a single moment, but rather incrementally via approximations or successive changes, and at times indirectly (Lindblom, 1992: 212).

Public debate occurs via language. Whether it is verbal or written, the argument is a central part of all stages of the public policy-forming process (Majone, 1989: 1). The arguments that are developed in the public arena generally do not adopt the form of rational analysis, but rather one that the Greeks called dialectic. The point of departure of dialectic is not an abstract assumption but rather points of view from the community; the conclusion is not a formal test, but rather a shared understanding of the issue under discussion. While scientific understanding is only available to experts, dialectic can be used by all, given that all can criticize or defend an argument (Majone, 1989: 6). As well as being a dialectical proposal and critique, the public debate is also composed of give and take of experimental and tested information (Dunn, 1994: 89). It is a dialogue between that which exists and that which should exist, each providing feedback via inductive and deductive claims between the interpretation of reality and that of theory and values.

Argumentation is made up of three types of claims or propositions: factual, value, and public policy (Rottenberg, 1994: 10). The point of departure of public argumentation is information and data; otherwise known as the factual claims which look to interpret and understand the reality. These claims are assumptions of reality and are derived from experience, from research and study, or from the opinions of authorities on the subject. A declaration that tries to be factual is, for example, 'water is even scarcer'. But the public debate is not completed by merely understanding the reality. Regarding these factual claims, value claims are made based on beliefs, values, priorities, and perceptions of the world. An example of this type of judgment is 'The scarcity of water in Hermosillo is critical and touches upon the human right to a dignified life and to meet basic needs'. These judgments not only presuppose certain factual judgments but also criticize and rank the facts related to a scale of values and priorities. Many propositions carry with them implicit values such as 'Hermosillo must continue to grow and requires new water-supply sources', which holds implicit judgments valuing growth, development, and urbanization, or perhaps determinism and fatalism, depending on how we wish to interpret them. The highest level of the argumentative pyramid corresponds to announcements or proposals for action: these are claims related to what needs to be done or for the adoption of a certain public policy. They are suggestions for policy development, such as

Table 32.1: Projects in an authoritarian and a democratic system. **Source:** By the authors.

	Authoritarian system	Democratic system
Design	Made in a closed manner where only governmental actors participate	Made with the participation of key social actors
Decision	Is an internal issue of the government, or where social support is manipulated	Is a result of public debate and participation
Information	Obscured. Not all the information is provided, only that convenient to the government	Transparent. There is openly available information regarding all aspects of the project
Actors that participate	Only governmental, contractors, and stakeholders closely related to the government	Governmental as well as any other affected group as well as the general public

proposals for construction of an aqueduct or desalination plant as solutions for water scarcity issues in Hermosillo. There may be many other diverse and real proposals that are not addressed.

The ability to put forward policy proposals constitutes a central part of the influence held by actors through time. In this case, the resulting decisions are not necessarily a product of a unique analysis and end situation or of a meeting where a persuasive case or explicit agreement is put into play. Rather, they often occur via a series of comparisons and successive approximations. The policy is not made once and for all, but rather it comes about and continues to evolve over time (Lindblom, 1992: 219).

On the other hand, the increasing opening up and democratization in the exercise of power is more difficult to document. Lintz and Stepan (1997: 15) suggest that no regime can be considered democratic if its leaders do not govern in a democratic manner. One line of research in this sense would be to observe how democratic the design and decision-making process for two large-scale public projects has been. The political theory of transitions and democratic consolidations suggests that one condition for democratic consolidation lies in the existence and development of a free and autonomous civil society, inasmuch as the state and civil society are effectively subject to the rule of law, that is, they adjust to existing legal frameworks (Lintz/Stepan, 1997: 17). With this observation, we may posit that an authoritarian government differs from a democratic one in the way that large projects are designed, decisions are taken, and information is released. In this way, the authoritarian government will offer to design a project internally and make decisions without consultation or social participation. They will not provide all the information regarding the project, but rather only what is convenient for the governmental actors and their allies. On the other hand, in a democratic system, the project is designed alongside key project actors, and this includes consultations with and participation by the involved parties. Also, as a result of the debate by both the governmental as well as the social actors, ample information is provided regarding the project and the decision (table 32.1).

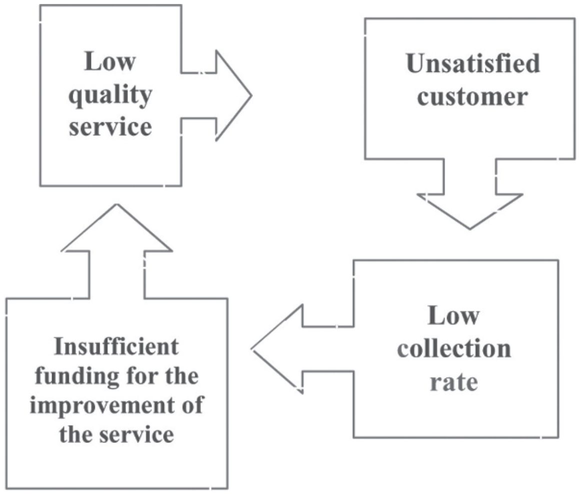
Hence the key to where to observe the democratization of the exercise of power is the participation of social actors in the design and decision-making of public work projects. The type of actors that participate, and the manner and occasion of their participation are also important.

In summary, the policies of urban management of potable water are not the result of a single and personal decision, but rather a product of exchange by a group of actors in the specified natural, cultural, social, and institutional environment. These actors use their power, resources, knowledge, and organizational capacity to influence and impose their own vision on public policy. The cases that follow allow us to revisit the validity of these theories, as well as the manner in which decisions are made and how policy is created in the specific environment of a Mexican city, during a period of economic instability and democratic transition.

A vicious circle in the management of water services occurs when infrastructure and pollution problems cannot be solved because of insufficient funding (figure 32.1). And there are no funds available because the tariff and revenue collection levels are low and they cover only urgent operational expenses. And collection cannot be improved nor the tariff increased because the deficiencies of the service do not justify these changes and the users reject any attempt at adjustment because of the deep-rooted belief that the government must provide the service for free.

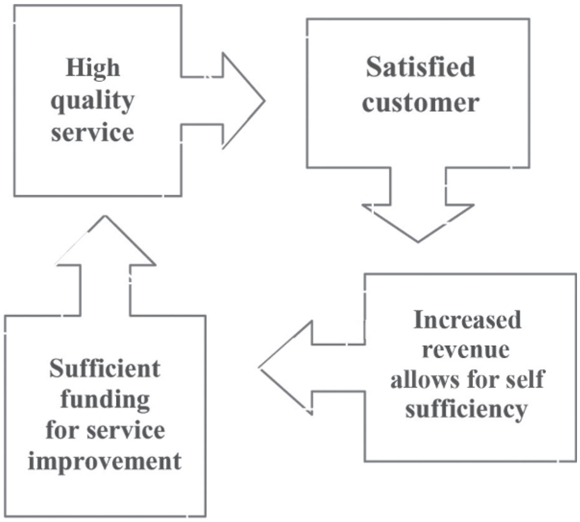
In order to prevent and avoid scarcity, pollution, and water conflicts it is necessary to break the vicious circle that affects many utilities. A low tariff causes the service to fall into a downward spiral. Therefore a virtuous circle must be started, based on a fair tariff,

Figure 32.1: Vicious circle of water services. **Source**: Elaborated by the authors based on: Mario O. Buenfil et al. (2003).



good quality of service, and a win-win relationship, where the customers obtain a good service at the right price, the utility is professionalized and acquires technical capability, and the authorities are legitimized (figure 32.2).

Figure 32.2: Virtuous circle of water services. **Source**: Elaboration by the authors based on: Mario O. Buenfil et al. (2003).



The variables that influence the performance of water utilities, the quality of the service, and the customer's behaviour can be classified into two types:

1. *Contextual variables*, such as water availability (hydrology, temperature, precipitation, etc.) and the particular features of a society (demography, economy, political regime, etc.).
2. *Institutional Variables*, such as the way the utility is governed and managed (governance), the way costs are funded, the level of social participation, as well as the rules, norms, procedures and customs that regulate water supply and distribution.

The study of institutional variables is a prerequisite for the formulation of public policies, so that an adequate institutional framework is designed in order to provide an efficient and sustainable water service.

32.3 Transition from a Traditional to a Self-sufficient Profile

A third line of research refers to the funding of the service and tariffs in the Mexican context. The sources for the funding of water utilities sways between two extremes: on the one hand, subsidies from the government; on the other hand, collection for the services. Between these two extremes there are many combinations of the proportion to which each source is used to fund the supply of water. Usually, utilities are funded both through revenue collection and government transfers carried out in the form of infrastructure investments and debt relief, among other things.

Based on these funding criteria, two profiles of utilities can be observed: the traditional profile, which is highly subsidized; and the self-sufficient profile, which is funded through revenue collection. A subsidized utility will depend directly on the government, being just another department within the local administration with a budget fully integrated into the government finances and management procedures fully dictated by government regulations. In this case, water revenue collection, if any, is merely symbolic, and is fully integrated with the treasury, that is, there is no separate accounting for the utility.

On the other hand, a self-sufficient utility is autonomous and has its own assets and accountability, and is managed separately from the government. In this case, the degree of independence and autonomy is measured through the proportion of its expenditure funded through revenue collection. This can be an entirely publicly-owned utility, a utility outsourced to a private company, or a partially or totally privately-owned utility.

Since the 1980s, water services in Mexico have evolved from the traditional profile of direct dependence on the government (usually as a department within the administration) into self-sufficient utilities (usually as a decentralized company) funded through revenue collection.

A disadvantage of a subsidized service is that it is provided at an apparently low cost to the customer, but is costly to the taxpayer, and can become a heavy burden on the latter. Another disadvantage is that there is no relationship of joint responsibility between the provider of the service and the customers, so the service is seen by the latter as a gift from the government: the customer does not fully pay for the service, demands no quality, and tolerates deficiencies.

Moreover, if water tariffs are not only low, but also fixed (i.e., the bill is decoupled from consumption) the customer will consume too much water, producing high levels of consumption and waste of water.

In contrast, in the self-sufficient model the service is provided by an independent utility that funds itself on the basis of revenue collection from the users, and the costs cannot go up because they are limited by the capacity of collection and the capacity of the users to pay. When efficient management exists, there is a tendency towards establishing a relationship of joint responsibility between the utility and the customer that affects the development of the professional and technical capability of the utility and increases the customer's welfare.

At the same time, variable billing based on increasing volumetric tariffs causes the customer to moderate his consumption. As in any other service, if one does not pay, the service is suspended or, at least, access to it is limited. Eventually, good planning, professional management techniques, and the efficient management of the resource will allow the utility to attain high levels of quality and reliability and an adequate level of revenue collection that can provide a better quality of life and economic incentives for local investment.

The most common case in Mexico is that of an intermediate profile between the traditional and the self-sufficient utility, which we will call a 'transition' profile. These are recently-created utilities that used to depend on subsidies, but which the increasing restrictions on the government's budget have forced to move towards autonomy. These organizations generally have an old and deteriorating network infrastructure that is near the end of its expected lifespan, a big payroll, and most of their expenditure goes on running costs. On the other hand, revenue collection is precarious because, although it is based on an approved tariff, it is not based on measured consumption, so that most of the collection is made on the basis of a fixed quantity. In addition, a lot of water is lost due to leakages in the network.

A large proportion of customers do not pay for the service and collection is not enforced, so debtors can still have running water even when they do not pay their bills. The income from collection by the organizations only covers the more urgent operating expenses and any infrastructure investment must be made with subsidies or bank credits backed by the government. Customers usually react angrily at any attempt to increase the tariff and are continually complaining of the bad quality of service. If customers do not perceive any intention to improve the service as credible, the service will further deteriorate until some crisis causes either a return to the subsidized model or a step forward to the self-sufficient model.

In the transition water utilities, revenue collection does not cover the costs. The tariff is not revised in order to cover the costs for the following period but only to try to cover the deficits incurred in the past. Tariffs are not calculated on the basis of cost recovery, and the utility only expects to collect whatever most customers are willing to pay. Some customers pay their bills whereas others do not. This system is unfair because it punishes the ones that pay by making them cover the costs of the service while it rewards free riders by providing them with water despite not paying for it.

In this process of transformation, the tariff is a main factor and an indicator of the degree of transformation and modernization of the water utility.

The tariff signals the type of relationship that exists between the provider and customers of water services. If the tariff is fixed and cheap and collection is not enforced, the message is that the customer can use water free of charge, and even waste it. If the tariff is well structured, based on the quantity consumed and collection is enforced, the message is that revenue collection is important for the support and improvement of the service, that customers must save water, and that they must pay in order to avoid enforcement. Tariffs are therefore an indication of the profile of the utilities and the behaviour of the customers.

32.4 Situation of the Water Tariffs

The handling of tariffs in the urban utilities of Mexico is in a state of total inertia. Studies of total recovery of costs are seldom carried out, and marginal costs are not estimated. Tariffs are only adjusted according to the inflation rate of the previous year and tariffs are

Table 32.2: Water services profiles. **Source:** By the authors.

Profile	Subsidized	Transition	Self-sufficient
Institutional Form	A department within government	Operating utility	Autonomous utility
Funding	Subsidies	Mixed	Revenue collection
Purpose of collection	Symbolic	Intended to cover operation costs	Intended to cover total costs
Costs	Increasing	High	Covered by tariffs
Quality	Low	High variability	Consumers demand higher standards
Tariff	Fixed	Mixed	Variable (based on measurement)
Collection efficiency	Low	Irregular	High
Penalty for not paying bills	None or is not applied	Irregular	Payments are enforced

increased by some additional margin only if the political circumstances favour these small changes.

Therefore, instead of calculating the requirements of running costs and investment in order to formulate a plan for revenue collection, utilities make a guess about how much can be collected and then expenditure is adjusted to the amount obtained through collection and subsidies. As a result, the standard of performance is that utilities do what they can, not what they should. There is no planning, and there is no projection of future requirements for operation and investment (table 32.2).

Ideally, tariffs should be designed on the basis of studies of costs and investment requirements. In 1989, the National Commission for Water (CONAGUA) adopted a policy that the directive boards of utilities were in charge of designing and approving water tariffs. This policy was based on the assumption that these supervising entities would be more inclined to care about the financial health of the utilities. Nevertheless, several legal actions have taken the approval of tariffs to the Supreme Court, which has ruled that in accordance with fiscal legislation, the payments for the water service are not 'products' but 'rights' that must of be approved by the municipal government and the congress of each state.

Thus, a technical entity was replaced with another entity with greater inclination to make political decisions and with an eye on election results as well. Therefore, technical studies for the adjustment of tariffs are not taken into account by the state congresses, and tariff increases or redesigns are refused because they could be politically adverse.

In addition to the problem of tariff design, there are problems of measurement and collection. The lack of metering of water in a large proportion of households means that a fixed quota is charged to these customers. This does not create incentives for saving water nor for repairing internal leakages in the customers' houses.

On the other hand, since there is no policy of disconnection from the water network for those customers who do not pay for water, many of them simply stop paying without facing suspension of their service. The result is that almost all the organizations have a long list of customers who do not pay the service, to the detriment of the water utility and the quality of the service. However, those same users always pay their electricity and telephone bills on time because otherwise the service will be suspended the next day. Therefore, it is unfair that the water service is maintained by the paying customers, who provide a sort of cross-subsidy to those who do not pay.

It has been argued that article 132 of the Health Law does not allow the disconnection of water services for reasons of public health. Even so, the National Commission itself has explained that this does not apply to those who do not pay for the service and it does not prevent the utilities from enforcing payments.

Nevertheless, although the water laws of most states allow disconnections, in practice they are never enforced. The result is that utilities cannot carry out an effective policy of collection, and on the other hand, it is the paying customers who maintain the service and, indirectly, subsidize it for those who do not pay.

32.5 Conclusion

In summary, the problems of water utilities, the model of independent and self-sufficient utilities proposed for their management, and citizens' participation in the strategic decisions of water utilities, are lines of academic research which can be addressed by answering the following questions:

- What elements are needed to adjust the institutional framework so that all Mexicans have a service of suitable and sufficient water in order to improve their quality of life?
- Why are most water utilities in Mexico trapped in the vicious circle of inefficiency and poor service?
- What can be done and what policy is necessary to establish a suitable institutional framework for the urban management of water? Is the model of self-sufficient water utilities an element in the attainment of this goal?
- Which regulations are an obstacle to the long-term planning and sustainability of water management?
- Which tariff schemes are fair? What characteristics must a tariff have in order to contribute to the efficient management of water?

These questions must be investigated to impel public policies towards the efficient management of urban water, and to increase its quality and sustainability.

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33 Institutional Barriers for Effective Water Governance in Mexico: Study of the Central Gulf Hydrological Administrative Region X

Judith Domínguez Serrano

33.1 Introduction

The concept of water governance has been built at the international level around two ideas: the analysis of the role of the actors with the aim of increasing their involvement in decision-making, and changes in institutions to facilitate this participation, in other words, on the role of the government, changing the rules and the various forms of water management. The aspect of this concept that has been most widely explored has been the analysis of communal forms of water management as a common property (Ostrom et al., 2000: 33). But in Mexico, little thought has been given to analysing the importance of the institutional framework (rules of the game) of this management to facilitate and promote the participation of all social actors (WHO, 2003: 32). This chapter focuses on the study of this framework.

The approach used for the analysis of the concept of water governance is institutional. Most studies neglect the role of the policy framework in its institutional and legal aspects. This chapter aims to gauge the participation of social actors within the 'rules' in force, and from this to propose amendments that would change the role that other social actors, unlike government actors, have traditionally played, so as to produce a more consensual decision.

Institutions are systems of rules, decision-making procedures, and programmes that result in social practices, that assign roles to participants in these practices, and that guide interactions among the actors in relevant tasks (IHDP, 2008). Thus, in order to bring about change in the role played by the actors in water management, it is necessary first to know how it works. For North (1990: 13), institutions are the rules of the game in a society or, more formally, the constraints devised by man that shape human interaction. Consequently, they structure incentives in human exchange, whether these are political, social, or economic. This refers not only to the study of formal rules, but rather to those that could be considered 'informal' insofar as they are not within a legally enforced framework, nor do they oppose it (Young et al., 2004: 5–7). Formal institutions coexist, as happens in Mexico, with social or community forms of water management. They may not even be mentioned in the law. In the case of water management, this reflects two realities, the legal reality and the one that has grown over the years, with a historical tradition deeply rooted in society. Within this 'dual reality' lies the implementation of solutions applied to the water problem through economic resources from the Federation. This research shows that the positive impact of these resources depends on the existence of a formal, clear, well-defined framework of action that all social actors are familiar with, and on the existence of local capacity for identifying the water problem, properly applying resources, and providing continuity for solutions. They are presented as conditions for improving local water management.

33.2 Background

The Rio Blanco river basin in the state of Veracruz (figure 33.1) was chosen as a case study for a project on legal, social, and institutional changes to water governance. This choice was based on the convergence of a broad set of problems of water management in this basin, including:

- intensive exploitation of water for agricultural, industrial, agro-industrial, and public urban use;
- representation of all types of pollution: industrial and domestic in the upper region, and agro-industrial in the middle and lower regions, with major ecological impacts all along the Rio Blanco and the Alvarado Lagoon;
- coverage of piped drinking water and drainage below the national average in both rural and urban

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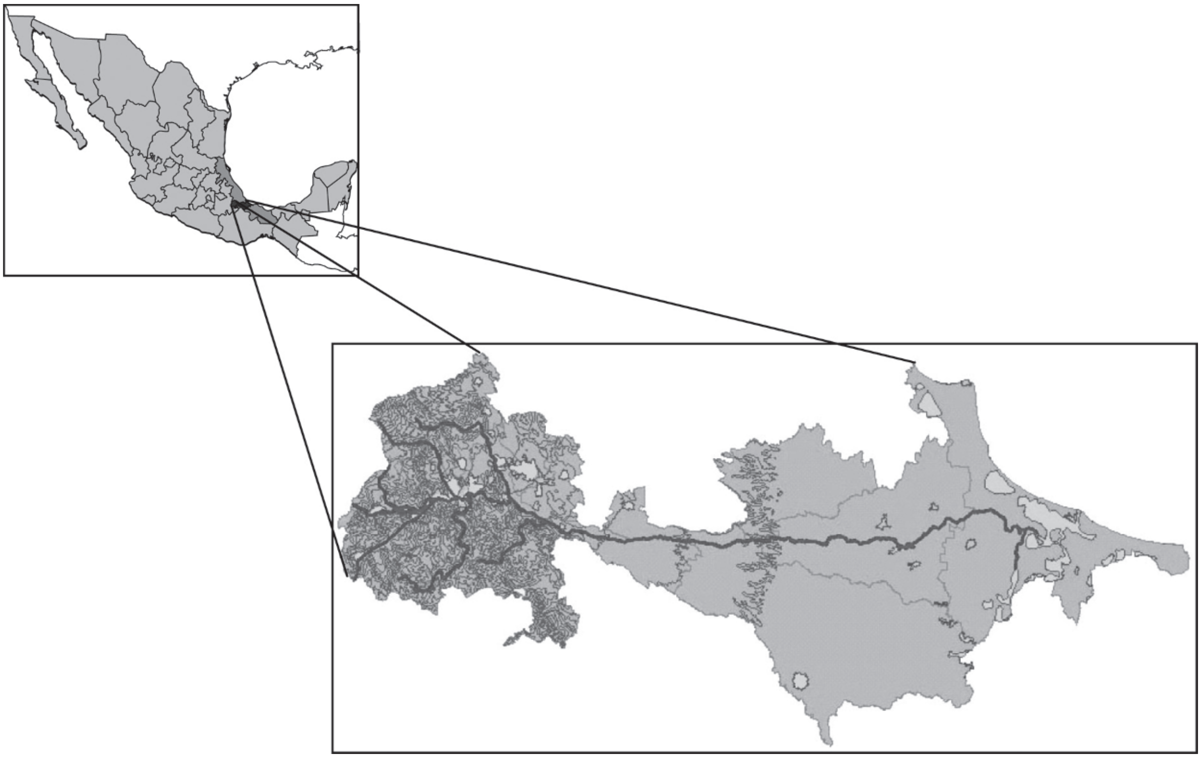
Figure 33.1: Study zone, showing location in the state of Veracruz, contours, urban areas, bodies of water and the course of the Rio Blanco and its tributaries. **Source:** The author.



environments, despite this being one of the areas with some of the highest availability of water;
- the presence of two metropolitan areas in the upper part of the basin, allowing inter-municipal water management to be undertaken;
- the presence in the upper part of the basin of preserved remnants of forests and jungles that are crucial to biodiversity and environmental services; and
- marked contrasts in the degree of marginalization of municipalities and locations.

The relevance of the study of this area relates to its identification by the *National Water Commission* (CONAGUA) as a priority area for action, because of the level of pollution. Some of the strategic programmes of the National Development Plan are flagship programmes, one of them being the Rio Blanco. The *Federal Environmental Protection Bureau* (PROFEPA) has also chosen this area for one of its programmes, named Clean Basin, and in this case it seeks to audit 37 municipalities – in two categories – on integral waste management and integral urban water management. There is political will to carry the project forward to the highest state level. CONAGUA intends to pour a substantial amount of money into these projects, which, with a pre-audit diagnosis in hand, would most likely mean better targeting of resources.

Region X contains the largest rivers in the country and paradoxically, despite being a region with high availability of water, is ranked 30th for potable water utility coverage, and 26th for drainage and sewerage (CONAGUA, 2008). To address this problem, several government programmes are being implemented, focusing on drainage, a clean river basin, and ecological zoning. This is therefore a very interesting case for analysis of the implementation of national water law, the implementation of the concept of water governance, and of the institutional capacity of governments and how they apply resources to address water-related problems. The qualitative research was designed to find answers to questions about local water governance in Mexico, exemplified by the public water service (drinking water, drainage, sewerage, and sanitation).

33.3 Objectives

This chapter pursues three objectives:

1. apply the concept of water governance to Mexico and make proposals that would facilitate its adoption;

2. analyse the legal, institutional, and programmatic framework for water management in Mexico; and
3. propose improvements in water management in Hydrological Administrative Region X in the Central Gulf.

33.4 Methodology

In order to become familiar with the institutional framework (formal), an analysis was conducted of the water law, the regional hydrological programme, and state programmes that affect water management. Three federalized programmes were also reviewed: the Clean Water Programme, which seeks to sanitise the sources of water supply in rural communities; the APAZU Programme supporting urban areas; and the PROSSAPYS Programme which is aimed at addressing the problems of rural communities. This analysis produced evidence that although the budget has increased over three years, it is not being applied to the areas most in need, and in many places the problem is not being dealt with.

We reviewed the programmes that the federal authorities have adopted in order to address the problem of pollution in the Rio Blanco: a) CONAGUA's Flagship Project to clean up the Rio Blanco River Basin; b) PROFEPA's Rio Blanco Clean River Basin Programme; c) the Veracruz state environmental authority's Ecological Clean-up of the Rio Blanco Basin; and d) proposed municipal measures for conducting an analysis of administrative and governmental coordination.

The Rio Blanco basin includes two metropolitan areas and 37 municipalities, of which 11 are adjacent and run into each other. Qualitative research was conducted in the 11 municipalities that make up the basin. This consisted of semi-structured interviews with municipalities and organizations operating in the upper part of the basin where the river rises, as well as with the state and federal water authorities. Participatory workshops were held with non-state actors to identify problems. This methodology mostly produces insights into the government's institutional capacity but also into that of other social actors, with a view to reversing the pollution situation and moving towards sustainable management of the basin. Even though these municipalities have conditions for regionally managing the water, they fail to do this. The causes of this lack of regional and medium-term vision for proposed local solutions are therefore being examined through interviews and questionnaires.

We studied data for the network of potable water, drainage, sewerage, and treatment provided by CONAGUA, along with data obtained on water statistics from the Census and Counts of INEGI for the period 2000–2008 in federalized backup programmes to deal with these issues, as well as data from the *National Ecology Institute* (INE) and other authorities such as the *Ministry of Environment and Natural Resources* (SEMARNAT) and the *Ministry of Social Development* (SEDESOL).

The proposed improvement of management starts by focusing on the basin, introducing the ideas of adjacent municipalities and metropolitan areas, and aiming at the effective implementation of the Water Act in line with urban development, in order to locate the solution among the modern ideas proposed in the international arena. This also stresses the importance of the social dimension beyond technological proposals.

33.5 Results

33.5.1 Water Governance as a New Framework for Action: Rethinking the 'Rules' for Stakeholder Participation

Although the concept of governance is increasingly becoming widely used, there is still no common understanding of the concept. The concept of environmental governance, or more specifically for the purposes of this chapter, of water governance, has not been well defined at the national level and is used to refer to many situations such as conflicts and mobility where water, its physical aspects, or community management are concerned (Corrales, 2004: 12). However, the concept is increasingly mentioned in documents from international organizations (Centre on Housing Rights and Evictions, 2007: 28–34) which directly or indirectly influence domestic environmental policies by suggesting new forms of participation and different social actors: the government, civil society, and private enterprise. The concept is still only vaguely understood in Mexico, and so this chapter analyses the issue, first to explain the concept, then to discuss local forms of governance.

One of the first changes in the approach to water resource management is the introduction of the two guiding ideas of: a) fairness in decision-making (Capel, 2000: 4) in water allocation and distribution, and b) solidarity in providing water to areas that do not have it. These two principles have not yet been introduced into our system of water law and have been the cause of great conflict. In the absence of formal rules, they must be incorporated into the management framework so as to recognize the way institutions are structured in different regions of the country. Not everything is covered by the legal framework. Opposition to the formal rules enshrined in the law and the 'informal' ones that are the product of social arrangements, or even arrangements with the authorities, is causing social conflicts over water management.

Management must be integrated and must take into account the environmental, social, physical, but mainly administrative limitations that modulate the concept (Helfrich et al., 2006: 19). Secondly, it needs to be understood that overcoming the crisis of governance is not solely the responsibility of government but involves the inclusion and participation of various actors in decision-making, depending on the role they play in society (inclusiveness), from planning (participatory planning) to implementation and especially assessment. Thirdly, environmental issues must be creatively addressed, and specifically water problems, in such a way that governance of its resources or governance as used in the Latin American context[1] refers to good water management and the participation of all stakeholders in shaping decisions.

Water governance[2] as understood here includes improvements in the institutional capacity, the legal frameworks, and the distribution of resources (Ostrom, 2000: 264). The concept also covers important elements in shaping decisions about water, such as the processes and behaviour that influence the exercise of power. Simply put, it is the inclusion in decision-making of all stakeholders (social partners) on issues that concern them. Therefore, the concept of governance implies openness, participation, accountability, efficiency, and coherence (as understood in the European Union).

UNESCO's (2006) second report on the situation of water resources in the world focuses precisely on the issue of governance of water resources, recognizing that this is where the water crisis lies, rather than in scarcity (Saleth, 2004: 84) or abundance of this environmental asset.[3] It recognizes the variety of governance systems that may exist in the world as there is no role model to follow. It is a matter that depends on the customs, policies, and conditions of each country, so that reforms with the aim of improving water management occur more as a result of internal pressures, environmental threats, population growth, and, a very important issue these days, the international spotlight.

For the *United Nations Development Programme* (UNDP, 2010) governance is the major precondition for an effective and equitable management of water resources with the objective of reducing poverty. In this area of study, lack of water is one of the integral factors of poverty.

The water problem in the Rio Blanco basin has less to do with the availability of water than with proper governance, the prioritization that occurs in public policy and the uses of water, fair equitable distribution, and conservation of acceptable quality for various uses. Consequently, reforms or the creation of new institutions to incorporate this concept of governance, as mentioned, involve the (re)creation of political, social, economic, and administrative systems to manage water resources (IMTA-OECD, 2008: 14) and ensure the equitable delivery of water-related services.

One of the biggest gaps in water management in Mexico is lack of participation, even in the National Water Act of 2004. If water governance requires dynamic interaction among the three levels of government, civil society, and the private sector, and is built on the political, social, economic, and administrative systems that directly or indirectly affect the use, development, and management of water, and the delivery of water-related services at different levels, then a better way should be sought for this participation. The incorporation of private enterprise has always been recommended by international organizations since there are functions and tasks that private enterprises can perform more effectively. The problem is how to internalize criteria (usually marketing criteria) into a

1 The Report on the situation of water resources in the world uses the term 'governance' in its Spanish version instead of the Spanish word 'gobernabilidad'. For the Royal Spanish Academy both words mean the same. They refer to the art or manner of governing in such a way as to achieve lasting economic, social, and institutional development, promoting a healthy balance between the state, civil society, and financial markets. However, some people differentiate these two terms, referring to governance as more of a Third World issue when they mention the existing lack of governance in Third World countries.

2 In the IV World Water Forum in Mexico (2006) it was recognized that there is "a crisis of governance, typified by poorly organized institutions, weak legal frameworks, limited human and financial resources, corruption and lack of transparency, and limited involvement of key stakeholders in the making of political decisions".

3 Final CONAPO 2000, with population projected to December, and CONAPO tariff and Grand Vision Water Plan 2001–2025.

legal and institutional system based on the notion of a public asset without altering the essence of the constitutional conception from which they derive. As for the social dimension, many studies show the 'local' effectiveness of locally-managed community systems.

Conceptualization includes the problem of how to promote more coordinated decision-making and how to improve communication between different levels, so that management is not top-down alone, but inclusive. The practical problem of water governance not only involves the incorporation of private actors or civil society, or legislative amendments. It depends on a number of social, cultural, environmental, and economic circumstances, so it is a problem of consensus, of how to reach agreements, transactions, and decisions between the various actors and in decision-making, and how to give power to a public entity or to other actors. The case study revealed that participation is reduced to a query about identifying a problem, and that there is more restraint when it comes to the adoption of solutions. It seems to be more of a search for seconding decisions already agreed on at the government level.

Water governance in its institutional dimension involves the integrated management of water resources or the integrated management of basins as effective management methods, and regional solutions can fit within that frame, as well as recognizing traditional forms of management for local areas.

At the 5th World Water Forum (2009: 17–19), the following issues were identified specifically on governance and management:

- implement the right to water and sanitation to improve access;
- improve performance through regulatory approaches;
- ethics, transparency, and empowerment of social actors, and
- optimize public and private roles in water-related services.

The first two aspects are addressed in this investigation, while how the last two can be implemented still remains to be defined.

33.5.2 Water Management in Administrative Hydrological Region X of the Central Gulf: Pollution and Deficits in a Public Service Network

Since the basin organization of Central Gulf Region X has not yet officially released its regional water plan for the period 2007–2012, the previous regional plan for the water programme for 2002–2006 for the region was studied. Various documents were consulted that describe what should currently be in force, and recent data from CONAGUA and the Census and Counts from the *National Institute of Statistics and Geography* (INEGI) were also reviewed.

The Hydrological Administrative Region X for the Central Gulf covers three states and the territory of 445 municipalities (figure 33.2). The region is also divided into five planning sub-regions[4] (table 33.1)[5]:

There are several problems related to water in this region, including pollution of water resources and domestic wastewater discharges into the upper Rio Blanco which represent a very important factor because in many areas they discharge directly into rivers, along with industrial wastewater in some specific areas, such as discharges from oil refineries or sugar mills. Another problem is the deficit in coverage; among its causes is the widely-scattered nature of rural populations in areas that are difficult to serve with the traditional infrastructure. These problems are associated with the impact of poor water quality on the environment and on health, and they have been a source of conflict over public service and, to a lesser extent, over pollution. This shows that the latter problem has not yet been identified by all social actors. But the former problem has not been dealt with by local authorities either; these opt for more visible projects (such as roads and bridges) rather than addressing those related to water infrastructure.

In Hydrological Administrative Region X of the Central Gulf, goals set for 2000–2006 that coincided with the National Water Programme (*Programmea Nacional Hídrico*: PNH) included the promotion of expanded coverage and better quality of service for drinking water, sewerage, and sanitation, as is the case in the states with the largest water deficit in Mexico (CONAGUA 2000, 2002). In Region X, one problem is the supply and coverage in rural areas where the population is scattered among over 24,000 localities; they suffer the greatest backlog in these services. The goal of the federal water authority in the previous programme was to achieve 56 per cent coverage by

4 Hydrological Programme by Agency in the Basin. Perspective for 2030. Hydrological Administrative Region X Central Gulf.

5 Definitive Census, 2000 with population projections in December with fertility rates from CONAPO and the Water Programme with Perspectives for 2030, Hydrological Administrative Region X, Central Gulf.

Figure 33.2: Hydrological Administrative Region X for the Central Gulf. **Source:** CONAGUA management, Region X (2000 and 2002).

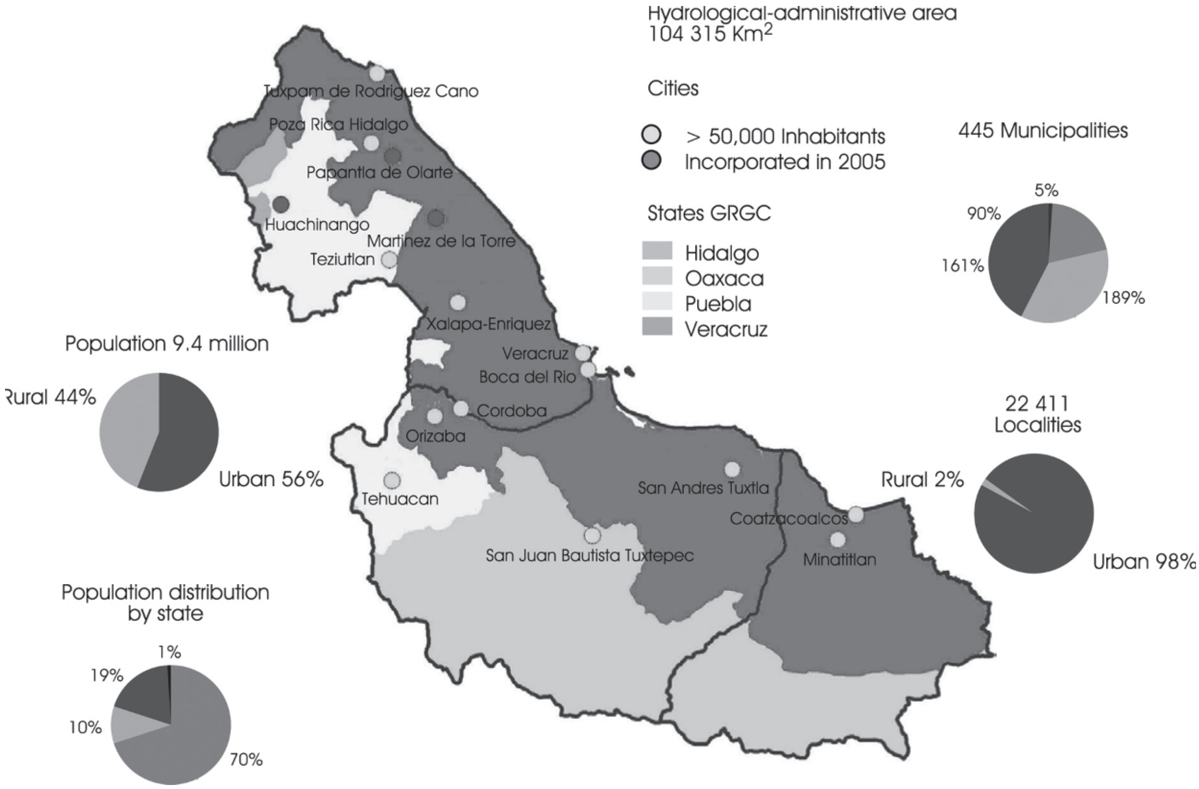


Table 33.1: Five planning sub-regions. **Source:** The author.

Basin council	Sub-region	Munici-palities	Municipal area (km^2)	Population	No. of basins	Hydrological area
Tuxpan to Jamapa	North	109	23,023	2,753,339	7	22,710
	Central	63	10,509	2,212,972	4	10,085
Papaloapan	La Cañada	80	12,240	637,801	2	11,088
	Mid Papaloapan	96	16,506	707,009	5	18,379
	Lower Papaloapan	63	18,777	1,789,726	5	16,324
Coatzacoalcos	Coatzacoalcos	32	23,576	1,116,070	7	28,103
Regional		443	104,631	9,216,917	30	106,689

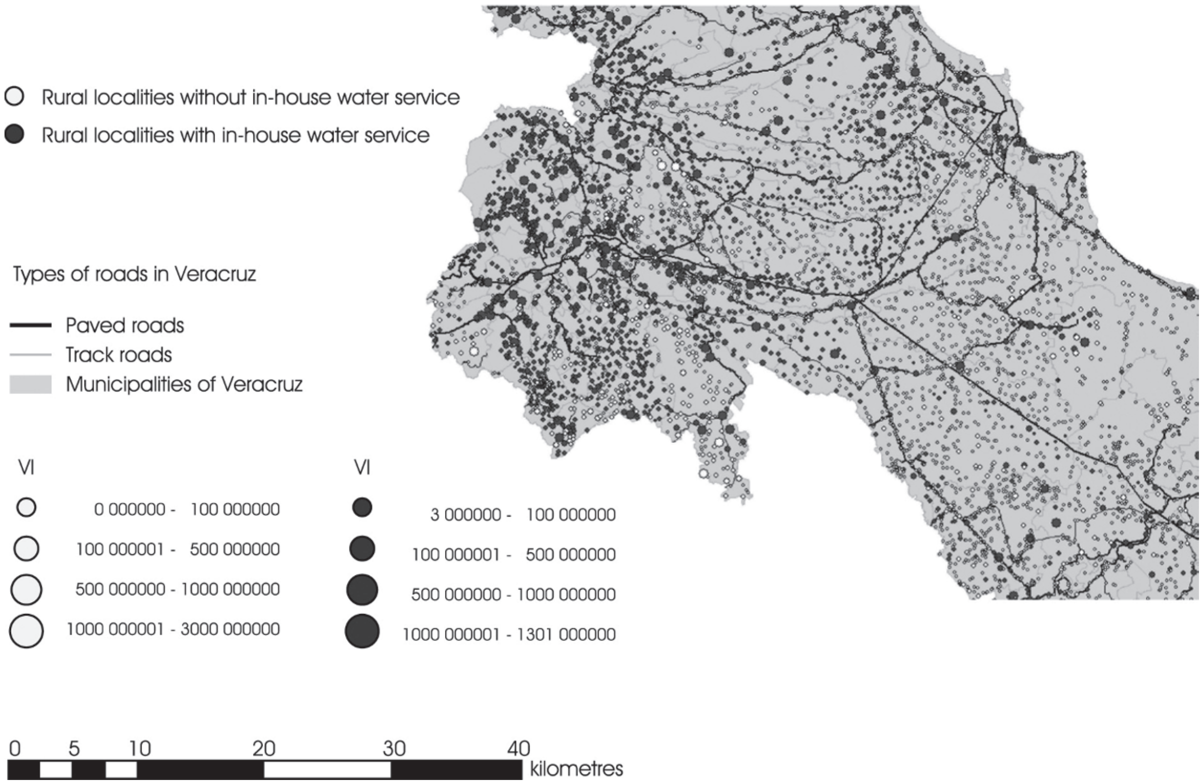
2006 for drinking water and 33 per cent for sewerage. It is important to note that coverage by 2000 was 54 per cent and 31 per cent respectively, according to the 12^{th} INEGI Population and Housing Census (2000). However, in this period we found no works identified or requested by municipalities to cover these items, indicating a lack of attention to this problem or even a lack of interest in dealing with it.

The study is being carried out in the state of Veracruz, even though Region X includes municipalities of other states, since in order to demonstrate the problem of public water service, preference was given to working with a single legal management framework. In Veracruz there are 5,983 localities where houses have no access to piped water (figure 33.3); 751,718 people live in these places (INEGI, 2005).

In 2,268 localities no property has drainage; 278,571 people live in these places (figure 33.4).

Given this situation and the large number of localities without service, the proposed actions are insufficient, because 370 rural drinking water systems for 5,983 localities without current service and 70 new

Figure 33.3: Sample of rural locations that shows those areas where houses have no access to piped water (light) and those where at least one house has access to piped water (dark). The size of the dots represents the total population. The road infrastructure is also shown (Presentation in ArcGIS 9.2.). **Source:** Author's research data.



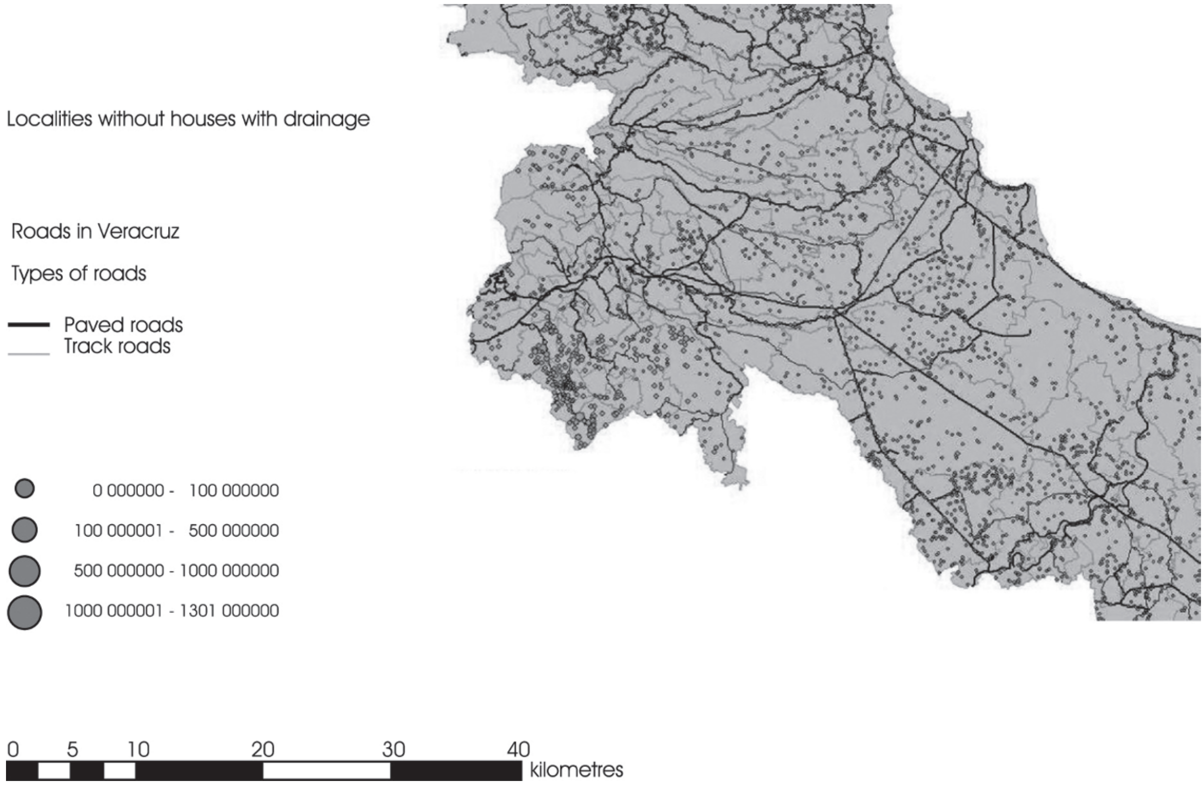
sewage systems for 2,268 localities will hardly be able to achieve the projected target (data from CONAGUA). Most importantly, the rural localities are widely scattered; the state authority is aware of this.

As for urban areas, information from the 12th INEGI Population and Housing Census (2000) shows that potable water coverage was 87 per cent and sewerage 85 per cent. The estimated coverage by 2006 was projected at 94 and 89 per cent respectively. The main water and wastewater projects waiting to be completed were concentrated in the urban areas (14 projects), but a review of how they helped overcome the deficit showed that by 2005 drinking water coverage (77.2 per cent) remained below the national average (89.25). The same applies to drainage and sewerage coverage; the national average is 85.6 per cent; 74.8 per cent have managed to obtain coverage here.

With the data from the INEGI Census and Counts (1995, 200, 2005) and CONAGUA's calculations, it is estimated that in Region X, 2,239,026 people have no formal sewerage service and 2,068,718 resort to self-supply by carrying the water themselves. Wells supply 1,503,413 of these inhabitants.

With regard to wastewater treatment and encouragement to exchange treated water for fresh water, eight projects were planned to reduce the pollution levels of the receiving bodies, but not all reached the stage of construction. This is one of the biggest problems in the region: either a job is not completed or it does not become operational due to a lack of trained personnel. In some critical cases, the treatment plant is constructed without the necessary infrastructure such as sewers, and this reveals the lack of a long-range vision, which ought to exceed the three-year municipal period. So, while there are several water treatment plants in the state, only between 30 and 40 per cent of these are in operation, and then not at full capacity. Few municipalities treat their domestic wastewater; the industrial sector has plants even though pollution exceeds their capabilities, because when a number of pollutants come into contact, the processes are insufficient, as is the case in the Rio Blanco region. The problem is the non-existent local management of this situation. One of the main findings of the research is the obvious lack of a local water

Figure 33.4: Sample of rural localities with no houses with drainage: the size of the dots represents the total population. The road infrastructure is also shown (Presentation in ArcGIS 9.2.). **Source:** Author's research data



policy because of legal loopholes and lack of institutional capacity.

The cleaning up of pollution caused by the discharge from sugar mills represents a major challenge for the state-level and regional management of water in this state. It has been decided that the cost of this operation should be covered by the mills themselves and that it poses potential conflicts. Ten of the 24 sugar mills do not comply with wastewater discharge regulations, and at the other mills, which do comply, there is the additional problem of the sediment liquid, whose legal character is not defined, thus leaving a vacuum in competence that leads to inaction by the authorities, and this has worsened the environmental problem. These examples are mentioned to highlight the incomplete policy framework within which solutions are being implemented, and this applies to the whole of Mexico, not only to the study area.

The Veracruz Development Plan 2005–2010 ranks the state in 24th place for coverage of drainage, and 30th place for drinking water coverage (figure 33.5). These data are not consistent with those of CONAGUA, since the latter's figures are higher with regard to its coverage. This is a further proven research finding: despite increased communication between the federal and state institutions with responsibilities for water, no uniformity of data is achieved.

The guidelines that were proposed in the 2005–2025 Statewide Water Plan were formulated by the *Veracruz Water System Council* (CSVA) and they were approved by the state governor in 2005. Besides referring to the construction of the necessary works of infrastructure, they seek funding schemes and the participation of society as a whole. In other words, essential actions should not be postponed through a lack of economic resources on the government's part. For rural areas the goal is to achieve 69 per cent potable water coverage by 2010 and 65 per cent for sewerage, and to achieve 95 per cent potable water in 2025, and 90 per cent sewerage (table 33.2).

In urban areas, the goal is to achieve 98 per cent potable water coverage by 2025, and 90 per cent for sewerage. By 2010, the expected levels were 89 per cent for both. However, federal resources are not addressing specific priority areas, and these are discussed below (table 33.3).

Among the most important causes of the deficit in coverage is the lack of efficiency of municipalities and of the operating agencies in identifying the problem and solutions (Furlong et al., 2008: 5). These agencies

Figure 33.5: Potable water coverage. **Source:** State of Veracruz (2005, 2005a).

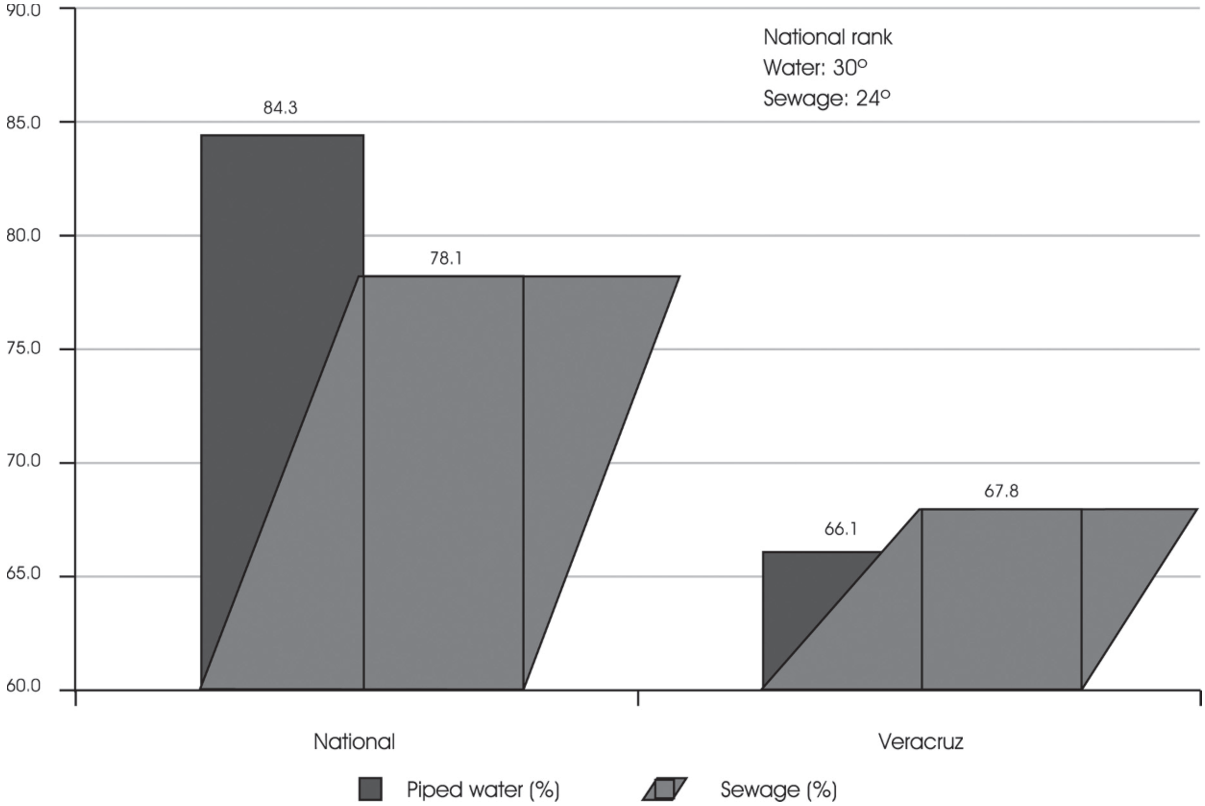


Table 33.2: Projection for drinking water, drainage and sewerage for rural localities. **Source:** State Water Commission of the state of Veracruz.

Potable water					
2000	2005	2010	2015	2020	2025
39.00%	53.88%	68.76%	77.98%	87.05%	95.00%
Drainage and sewerage					
2000	2005	2010	2015	2020	2025
31.00%	40.69%	64.67%	73.11%	81.56%	90.00%

have (in the area studied) neither sufficient staff nor trained staff (except for the large municipalities of Cordoba and Orizaba), they operate with negative balances, and pricing efficiency is zero. A clear example of this is the state of Veracruz, as shown in table 33.4, which illustrates inability to measure the supplied product and to collect payment for it. This becomes a vicious circle where the low collection amount is blamed on poor service, a situation that prevents the operating agencies from improving service due to insufficient resources (European Commission, 2006: 34). Other aspects of the low amounts that were collected have also been identified: (1) charges do not represent the needs and actual costs of agencies; (2) customer lists are incomplete and outdated, thus encouraging illegal water use; and (3) the low coverage of micro measurement requires approximate estimates to be made of probable consumption and of the functioning of the systems in general.

In the above table, figures for the largest urban municipalities in the state show that the percentage of water unaccounted for is approximately half of the volume that was extracted, as well as that the collection per capita in some locations is well below the national average, with only three locations being above this level. However, in collection per cubic metre, Veracruz is the only city above the national

Table 33.3: Projection for potable water, drainage and sewerage for urban localities. **Source:** State Water Commission of Veracruz State.

Potable water					
2000	2005	2010	2015	2020	2025
80.00%	84.55%	89.10%	92.11%	95.34%	98.00%
Drainage and sewerage					
2000	2005	2010	2015	2020	2025
86.00%	87.35%	88.69%	90.79%	92.90%	95.00%

Table 33.4: Supply of water and collection of payment. **Source:** State Water Commission of Veracruz State.

Locality	**Collection 2001**		**Inhabitants attended**	**Water produced m³**	**Water invoiced Total**	**% Water not registered in the accounts**
	X inhabitant	**X m3**				
Xalapa – Enriquez	142.8	1.3	364,191	9,898,848	5,073,455	48.75
Veracruz	239.98	2.35	641,383	17,033,328	8,990,700	47.22
Orizaba	3.45	0.02	81,107	N/D	N/D	N/D
Córdoba	125.5	0.87	153,907	4,502,220	1,660,755	63.11
Poza Rica	168.31	1.21	137,402	4,803,500	3,568,613	25.71
Coatzacoalcos	220.07	1.51	229,834	6,351,327	3,680,487	42.05
Minatitlán	208.61	1.33	111,872	3,579,382	1,754,932	50.97
Tuxpan	157.8	1.33	71,806	2,133,953	565,491	73.5
San Andrés Tuxtla	81.03	0.85	49,165	N/D	N/D	N/D
Martínez de la Torre	21.1	0.2	44,970	N/D	N/D	N/D
Coatepec	78.13	0.49	42,803	N/D	N/D	N/D
National	196.58	1.73				

average, and this emphasizes the need to administratively reorganize the operators of the agency.

In Veracruz, and in the rest of Mexico, municipalities with high and very high degrees of marginalization are mainly rural, but it is striking that in the municipalities in the metropolitan areas of Orizaba and Cordoba, for example, it is common to find high and very high marginalization. The interviews revealed that in Mexico more chlorinated water is provided than drinkable water. The number of treatment plants is 541 in Mexico (CONAGUA 2007) and 8 in Veracruz, and the procedures used are intended to remove elements from the water (hardness, organic traces, suspended solids, or dissolved solids). This is why the water is not suitable for direct consumption, even though in deprived areas it is often used for human consumption and so is linked to diseases related to water quality. This has caused a problem of considerable magnitude in terms of equity in access to water, which will not be discussed here, but whose main points can be summarized by referring to two issues, equality of access to drinking water, in terms of both quality and quantity, and equity in the payment of the water that was supplied.

Much of the domestic discharge in the greater metropolitan area goes directly into the river. However, attention should be focused on the upper zone where the industrial discharge from chemical and paper plants, distilleries, sugar refineries, and breweries pollutes the river. This study identified municipalities where untreated municipal discharges predominate, in Alcutzingo, Cuchiapa, Cuitlahuac Ixtaczoquitlan, Maltrata, Nogales, Camerino Z. Mendoza, and parts of Orizaba. Cordoba has pollution from the municipal slaughterhouse, municipal and industrial discharges (distilleries), and in some areas indiscriminate use of herbicides, which generate the bulk of the pollution entering the Rio Blanco. In Nogales, however, it is the landfill and pig farms that generate most pollution. Finally, in the Rio Blanco the main source of contamination is the General Hospital and the municipal slaughterhouse. These municipalities constitute

Table 33.5: Legislation on water and distribution of responsibilities. **Source:** Developed by the author.

Federal	National Water Law	(Article 9) CONAGUA: Encourage and support urban and rural public services of water supply, sewage, sanitation, recycling, and reuse in the country, to which end it will coordinate with the state governments, and through them, with municipalities. (Article 9)
State level	Political Constitution of Veracruz	Agree with the municipalities that the state assumes responsibility for the implementation and operation of works and provision of public services to be supplied by municipalities, and agree for them to be in charge of one or more of the functions, or execution and operation of works and provision of public services that correspond to the state. (Article 49)
	Water Law of Veracruz	Provide, in the municipalities, public services to supply potable water, drainage, sewage treatment, and disposal of wastewater, upon agreement with the municipality concerned and, in this case, establish and collect dues and fees incurred by the provision of services. (Article 15)
Municipal level	National Constitution	Municipalities will be responsible for the following public functions and services: a) Drinking water, drainage, sewage treatment, and disposal of wastewater; c) Clean-up, collection, transfer, treatment, and final disposal of waste, f) Slaughterhouse. (Article 115)
	Political Constitution of Veracruz	Municipalities will be responsible for the following municipal functions and services: a. Drinking water, drainage, and sewage; c. Clean-up, collection, transfer, treatment, and final disposal of waste; f. Slaughterhouses; i. Promotion and organization of society in urban development planning, cultural, economic, and ecological balance. (Article 71)
	Water Law of Veracruz	The municipalities, in accordance with the provisions of the Organic Law of Free Municipalities, and other state laws, shall provide, either directly or through the appropriate operating agencies, the public water supply, drainage, sewage treatment, and disposal of wastewater. (Article 3) Municipalities may grant total or partial concession of public services of drinking water, drainage, sewage treatment, and treatment and disposal of wastewater. They may grant total or partial concession of municipal public domain property constituting the hydraulic infrastructure needed to provide the services; or for the full construction and operation of the service system; for the construction, operation, and maintenance of treatment plants and disposal of wastewater and sludge management. Authorization to provide service of pipes, potabilization, supply, distribution, or transportation of water. (Article 47)
	Municipal Organic Law	Grant concessions to individuals, subject to State Congressional authorization of the State in the manner stipulated by this law, for the provision of municipal public services. (Article 35) Be responsible for the following functions and public municipal services: a) Potable water supply, drainage, sewage treatment, and treatment and disposal of wastewater; c) Clean-up, collection, transfer, treatment, and disposal of municipal solid waste; f) Slaughterhouses; i) Promotion and organization of society in urban development planning, cultural and economic development, and ecological balance. (Article 35) The provision of services is of public interest. These will be general, sustained, regular, and uniform. (Article 93)

the upper Rio Blanco river basin, and this is where resources will be applied first, since by the time the river flows out in Alvarado it is filled with pollution produced upstream. It has caused damage to the fishermen in this municipality in particular.

There are 13 wastewater treatment plants in six of the 37 municipalities bordering the Rio Blanco (Alvarado, Amatlán de los Reyes, Cordoba, Fortin, Ixtaczoquitlan, and Rafael Delgado) with a total capacity of 1,316.92 litres per second. The average capacity of the six plants is 220 litres per second. Yet the flow treated is only 60 per cent of the installed capacity (809 litres per second). These data allow us to gauge the size of the problem faced by authorities wishing to clean up the Rio Blanco.

33.5.3 The Rules of the Game are not Clear: Incomplete Legal Framework and Lack of Definition of Competence

Another of the items discussed was the legal framework for action. Ensuring public water service in Mexico is the responsibility of the municipalities according to article 115 of the Constitution, and according to the following distribution of responsibilities (table 33.5).

Given the inability of municipalities to provide the service, the state government agency of the *Veracruz State Water Commission* (CAEV) takes on this service and often absorbs the debts they have. The same thing happens in the case of treating municipal waters in the metropolitan areas of Cordoba and Orizaba which, through the water authority or environmental authorities, are responsible for the treatment process, and even with this advantage cannot manage to treat wastewater completely. Thus we see a large number of operator entities under their jurisdiction; rarely are they municipal, especially in large municipalities. Note that in this state some 'community' operator agencies are acknowledged in areas of rural or indigenous population or where springs are located and where adherence to the law is highly questionable, when the municipal authority has acknowledged they have a right to them.

Although there is a state water law, it has regulatory gaps that hinder sound management (Global Water Partnership, 2002: 3), and this is complicated by the lack of regulations to implement the national water law. State law focuses on defining the functions of the operator agencies. It recognizes inter-regional or para-municipal methods in the provision of public water service, and yet there has only been one experience of this in the state: the Veracruz–Boca del Rio Medellin Inter-Municipal Agency Water and Sanitation System. Despite favourable conditions for regional management in the area studied as a result of conurbation, para-municipal methods are not present in the solutions that appear within the area's municipal boundaries. In this area there are no municipal provisions governing public service, except as provided for in state law. The operator agency has experience in managing the problems on a day-to-day basis.

33.5.4 Lack of Coordination of Programmes and Authorities

A serious problem in the state is created by overlapping programmes of the three levels of government that address the same problem, not only for water issues but also for environmental or regional programmes such as tourist programmes, in which resources are granted with no regard for the effects they cause or for coordination with others, even within the same municipal authority.

For example, in the Rio Blanco river basin, in order to deal with the pollution problem the three levels of government (federal, state and municipal) have proposed various measures. On the initiative of the federal authority (CONAGUA and Federal Environment Ministry, through the attorney for environmental audits) different solutions were proposed. The first consists of devoting huge resources to the problem, but without prior diagnosis (this is taking place at the same time as the solutions are being implemented). The second, without using resources, consists of working through the power of 'persuasion' to enter the environmental audit programme. Without entering into the legality of these certifications, such as the 'Clean Basin', the expectations generated at the local level are unrealistic because they will not solve the problem as outlined in the short term. That in itself contributes to the lack of credibility in institutions. Local authorities have already requested resources and have been granted them for the construction of several wastewater treatment plants in the region, without a previous diagnosis, without consideration for urban plans, without any assessment of the social impact, and without public consultation. They are subject only to the deadlines for requesting the budget. Thus, it is quite likely that, once again, resources will not be applied effectively. What is the problem? Neither the federal, nor the state or local authority has understood what local environmental management entails. And a local water policy in the region simply does not exist.

To demonstrate the lack of capacity, the problems small municipalities face are illustrated when they have to apply for federal funding. First, they must find out if funds do exist, understand the rules of operation, and then try to fulfil the requirements.[6] One is that for the application to be successful, the federal entity must sign an agreement of federalization and decentralization with the federal government, and this, as officials from CONAGUA have indicated, is a

6 Potable Water, Sewage and Sanitation Programme in Urban Zones (APAZU), Programme for Construction and Rehabilitation of Potable Water Systems and Sanitation in Rural Zones (PROSSAPYS), and Clean Water Programme (PAL).

problem because governments allow the established deadlines to lapse, sidelining them from the 'game'. This prevents municipalities and operator agencies from seeking the support contemplated in the programmes.

The lack of adequate communication mechanisms between the state and its municipalities indicates the requirement to successfully target resources towards urgent needs in each location. That is why we often see that the works are not completed or are not suited to the geographical, hydrographical, and institutional situation of the municipality or locality. Table 33.6 shows the results of two aspects included in the interviews:

The overlap of programmes, with no coordination with each other (because each authority is trying to show it has solved the problem), has led to a duplication of functions and resources. At present, environmental planning is not being considered in the proposed location of treatment plants. Technology is seen as being able to provide a solution, with a proposal to install treatment plants along the river. However, social protests have already emerged over the abandoning of the social dimension of the water problem. No one knows what the problem is that needs to be addressed, and the project has not been discussed with the participation of all the actors.

Possibly, however, they have simply put things on hold, because while the municipalities are already calling for bids for construction of the project, CONAGUA is starting to identify the social actors. On whose shoulders then does the solution depend? Who is the authority on water? How can one ensure the effectiveness of the measures if they have not even been consulted at one level (the government)? These are questions to be addressed when talking about governance. And this chapter shows the lack of implementation of the concept behind the *integrated management of water resources* (GIRH in Spanish).

33.5.5 Lack of Institutional Capacity in the Water Authorities: Functions, Budget, and Long-term Vision

The lack of institutional capacity in municipalities represents the main obstacle to the success of programmes. The rules of operation of the support programmes establish and encourage not only attention to the construction of works, but also their continuity and maintenance. And those who should do this work are the municipal authorities or the operator agencies. However, as stated in the analysis of municipal management that was conducted in this investigation, there are none of the human, technical, or financial elements nor intra- or inter-municipal relationships necessary to achieve this end.

Interviews were conducted in the Rio Blanco Basin region which clearly show that most municipalities do not have the institutional capacity to address the pollution problems that exist, for several reasons: either they are unaware of the real problems, or they do not have the human or financial resources, or do not see the issue of public water service as a priority. So the institutional aspect is one that deserves greater consideration when applying federal resources.

During interviews in the 11 municipalities surrounding the metropolitan areas of Cordoba and Orizaba it was noted that on the issue of internal inter-municipal coordination, six municipalities highlighted the fact that there was no communication with other departments regarding the environment (i.e. Public Works, Potable Water Supply). Only two municipalities (i.e. Cordoba and Maltrata) mentioned coordination existing between similar departments. However, the authorities of Maltrata noted that there are no joint programmes between these areas. In some municipalities such as Rio Blanco, Nogales, and Camerino Z. Mendoza, it is not known whether coordination exists with other similar departments.

In terms of conditions of the water infrastructure, four of the eleven municipalities referred to this issue. These four municipalities (i.e. Cuchiapa, Ixtaczoquitlan, Veracruz, and Maltrata and Rio Blanco) agree that the infrastructure is very poor and very old. In Ixtaczoquitlan there are multiple leaks and clandestine water use.

With regard to water conflicts in Alcutzingo, a municipality with a high degree of marginalization, there are conflicts in communities of over 1,000 people in the upper area that is supplied by water from tanker-trucks. Importantly, in this area there are many springs. Also in Ixtaczoquitlan, the community has registered protests over the state's largest treatment plant, the FIRIOB, built just a few metres from several secondary schools and high schools, which reveals the lack of urban, not to say environmental, planning. In addition there have been numerous conflicts over water supply and pollution of the rivers from which the supply comes. In Nogales, because of the deficient service, some communities independently organize their drinking water supply, and there have been several protest movements. In light of the deficient service, community pressures in Orizaba came from the

Table 33.6: Determinants of local water management. **Source:** Developed by the author.

Municipality	Internal coordination	Conditions of the water supply infrastructure
Acultzingo	There is no coordination between departments. There are meetings between the irrigation units, in which they exchange experiences on their systems and implement new projects. There is no management for ecology or the environment; these issues are addressed in the area of agricultural development.	Communities of more than 1,000 inhabitants in upper parts of the municipality are supplied by water delivered in tanker trucks (Tinotla, Coatepec, Ahuicide); deforestation.
Cordoba	Communication between the areas of ecology, environment, public clean-up, and operator agency.	Areas with deficit in coverage are in the outskirts, due to urban growth.
Cuichapa	No management of the ecology. Such issues are handled under agricultural development and farming, but little importance is attached to them.	In poor condition, very old.
Cuitláhuac	They show interest in coordinating with adjacent municipalities. There is no internal coordination in the formulation of programmes or policies.	
Ixtaczoquitlan	Direct contact with council-woman and ecology board; no knowledge of the actions of other departments related to the environment, waste, and water.	Multiple leaks in water pipelines from the municipal capital; clandestine power taps/outlets. The drainage is very old and in bad condition. Most domestic waste discharges go directly into the river. Although the FIRIOB treatment plant, one of the country's largest, is in this municipality, the collectors were not built to connect the municipal drainage to this plant. They have not paid the treatment processing fee in 10 years, because it was calculated based on a population growth that did not happen.
Maltrata	Communication between the areas of education, industrial development, public works, public clean-ups, and ecology. However, no joint programmes on water, except water culture.	Very old, in bad condition.
Nogales	There appears to be no communication between the collecting areas; no knowledge of actions and programmes implemented by other departments.	Some of their discharges are connected to the FIRIOB plant, and others go directly into the river. Problems with the municipal slaughterhouse over its discharges.
Orizaba	The Department of Public Works handles water and sewage, but there appears to be no clear link with the environment department, inasmuch as from an interview with the director of ecology it was obvious there was no knowledge about programmes for development.	Good coverage; on the outskirts the municipality supplies free truck-transported water. There have been protests against a rise in the price rate, even though it is one of the lowest in the region.
Rio Blanco	The ecology department has direct coordination with the mayor; however, they are unaware of programmes or activities of the various areas. That is not the case with the operating agency, which works on its own, despite being municipal.	Very old, in bad condition. Water arrives in smaller quantities than required because it remains in the two municipalities in the upper region of the river.
Fortin	There is no coordination with water management. The operating agency is state-run.	Coverage problems in many parts of the municipality.
Camerino Z. Mendoza	No coordination with the manager of municipal waters and the operator agency, for political reasons.	This is the first municipality to benefit from river water and direct discharge into the river, being the first urban municipality in the upper part of the basin, meaning pollution travels downstream. It was disconnected from FIRIOB for lack of payment for several years. It is the municipality that sees a joint proposal with the adjacent municipality as viable, but only for political reasons.

middle and lower regions, as well as from some users in agribusiness.

Some councils are negotiating to restore the operator agency, but most operate in the red. With this background the question arises, how do the authorities intend to implement medium-term measures if there is an obvious lack of coordination and lack of institutional capacity in environmental management and specifically for water?

33.6 Conclusions

1. The concept of water governance must include the analysis of the institutional framework, within which proposals for participation by various social actors have a place. Understanding and knowing about this framework is essential, as stated in this chapter, because it determines the effectiveness of measures to be taken by the actors.
2. In Mexico there are barely-studied hydrological administrative regions with serious water problems. More regional analysis is therefore required. The Central Gulf Region X has not been studied from the institutional standpoint. Technical-environmental studies exist but the institutional, legal, and social dimension have not been examined in any depth, other than finding evidence of conflicts. The municipalities in southern Mexico show serious deficiencies in management, as opposed to the successful experiences in north Mexico. There is an urgent need to address this diversity and build capacity in these areas, which is where major problems in management exist, but also where water resources are physically located.
3. The problems in the coverage of public water service can be traced back to the following issues: overlapping of programmes of various ministries or decentralized agencies (SEDESOL, Tourism, SEMARNAT, CONAGUA, PROFEPA) with state-run programmes; lack of coordination; or lack of infrastructure, staff, or resources for water. There is also a lack of intra-municipal communication and communication with higher levels, and where it does exist, the proper channels are not being used. Another deficiency is in the provision of service and the pricing assigned to it.
4. There is poor administrative and inter-governmental coordination in solving water problems, leading to inefficiency in resources and the lack of resolution of the problem. Regional approaches to addressing problems must be promoted, using the experience of north Mexico or of the municipalities such as Coatepec in the state itself, and maximizing the conurbation status in areas such as Rio Blanco.
5. It is necessary to address capacity building of local environmental management to ensure sustainable measures in the long term and therefore sustainable management of water basins. Until then, there are immediate solutions for 'patching up' a problem, which will be resized later. This capability includes the strengthening of formal institutions and the recognition of those that coexist alongside them; training in local environmental management issues; and the creation of mechanisms for communication and information among all stakeholders.

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Concluding Remarks

34 Concluding Remarks

Úrsula Oswald Spring

34.1 Introduction

These conclusions do not pretend to summarize the richness of the book. They rather seek to highlight the most important issues related to water and water research discussed in the framework of the overall project of the Scientific Network on Water (CONACYT), including the meeting in Cocoyoc in January 2009 and the one in Cuernavaca 2010, as well as the papers presented there. This book is a first attempt at offering an inter-institutional and multidisciplinary dialogue on water. Given the complexity of the topic, it is an important first step in that direction. The authors and the editor have tried to keep the most integral vision possible and to integrate existing research and research webs. This book establishes a state-of-the-art diagnosis of water research in Mexico and reviews the most pressing issues.

These concluding remarks are grouped around seven thematic axes that seek to maintain an integral socio-environmental vision while at the same time taking into account the most vulnerable social groups. In that sense, the book represents a critique of past water management in Mexico, where hydrological and civil engineers consumed important natural resources and where peasants and indigenous groups were forced to give up their ancestral rights and lands and to hand them over in the name of a 'progress' that often failed to deliver and that helped to further concentrate wealth in the hands of a select group, leaving more than half of the country's population in misery.

34.2 Some Results and Areas of Potential Research

34.2.1 Socio-environmental Complexity: Surface and Groundwater in Various Ecosystems Affected by Climate Change

From the start, the book has sought to link water with other natural resources, with its importance for human activities, and with its effect on well-being in various sectors of Mexican society. These interactions, some self-regulated and some chaotic and unpredictable, some positive while others are negative, can be theoretically systematized by an environmental quartet which makes the interrelationship between water, atmosphere, biota, and soils explicit (figure 34.1 and 1.1).

Even when each of these natural resources represents a single cycle with its own dynamics and associated vulnerabilities, the great cycle of climate change can exacerbate water-related stress. It impacts on the yearly availability of water (in dry and rainy seasons), and the effect is severe in central and northern Mexico (SEMARNAT, 2006, 2007). Together, these dynamics can affect biodiversity, and it is possible to reinforce, limit, or even transform the effects. As a result, Mexico faces a process of desertification, land degradation, and salinization (UNCCD, 2009), reducing the growth capacity of plants and affecting evapotranspiration, thus impacting on the water cycle and consequently on the overall availability of water (chap. 7 by Garatuza et al.). As the soil gets drier, it has less groundcover, and this reduces its capacity to reduce *greenhouse gases* (GHG), leading to higher temperatures, changes in rainfall patterns, more severe hydrometeorological events (hurricanes, tempests, droughts), and changes in agricultural and crop productivity, i.e., changes in resistance to plagues, fungi, and disease.

The goal of integrating the well-being of societies in this book translated not only into accounting for the availability, consumption, quality, and different

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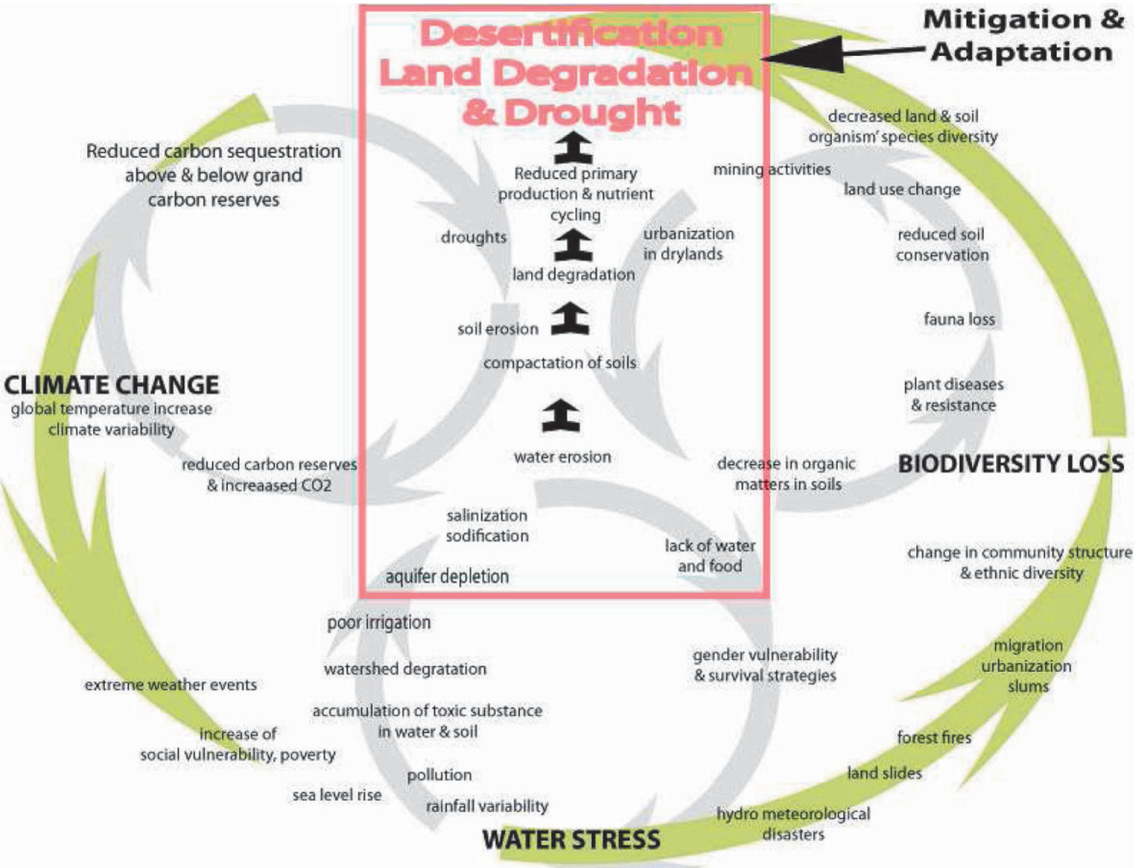
Figure 34.1: Complex interrelations within the 'environmental quartet'. **Source:** Brauch and Oswald Spring (2009: 12).



uses and habits among Mexicans, but also into seeking to understand the deep and contradictory interactions between this 'environmental quartet' and social dynamics: social stratification, different uses of water, conservation versus waste, pollution, and mechanisms that force users and authorities to manage water responsibly and foster collaboration between the three levels of government, and that include all stakeholders together with the negotiation mechanisms of their specific interests, whether for the sake of communal well-being or private gain. From this standpoint, the complexity of the interactions between the 'social' and the 'environmental quartet' call for an integrated approach to water (chap. 12 by González et al.) with an interdisciplinary methodological and analytical basis.

34.2.2 Trans and Interdisciplinarity in Water Research: An Integrated Vision with Scientific Rigour

Trans and interdisciplinarity is not only a juxtaposition of specialists studying a topic from their own particular perspectives; it means establishing new conceptual discussions, tools, and results surrounding a research topic that no single discipline could have reached alone. In this book, this has meant integrating not only hard science experts such as engineers, hydrologists, chemists, and physicists, but also social scientists, lawyers, economists, political scientists, architects, landscape professionals, and environmentalists.

Linking water with the environmental quartet in an interdisciplinary fashion meant transforming the analysis of specific scientific fields as well as of individual actors (often linked to very particular interests such as businesses, government departments, and multilateral institutions) towards a different paradigmatic model centred around socio-environmental sustainability with quality of life and human (Brauch 2005), gender, and environmental security (Oswald, 2008, 2009a; Oswald/Brauch, 2009, 2009a, 2009b). The initial debate was about how to launch a dialogue across disciplinary boundaries and to profit from the diversity of the methodological approaches at hand. This dialogue also includes various stakeholders with different and often conflicting goals, interests, and missions (chap. 23 by Oswald; chap. 24 by Germán/Escobedo). Facing this dilemma of postmodern understanding, it was decided to give 'voice' and participation to all the actors involved in water management. Scientific, administrative, political, and social knowledge is valid, useful and complementary. This is the novel proposal of this book, to link a vast array of knowledge and everyday practices into a rigorous interdisciplinary outlook with the firm goal of envisaging the bases of a novel water culture that includes agents, practices, and knowledge. It means integrating social and natural cycles concerning water.

This approach seeks to overcome the rigidity of positivism and its understanding of 'exact science' (Popper, 1994; Kuhn, 1962; Prigogine, 1994) at the same time as paving the way for deconstructing and reconstructing new knowledge oriented towards a more integrated water management. The book includes a long-term perspective, as new risks and challenges have triggered other processes of mitigation and adaptation, where it is hoped to offer environmental services to a growing world population without further ecological destruction and without marginalization of the most vulnerable social groups. This process also implies a new ethic for understanding and managing a vital natural resource that is becoming increasingly scarce and polluted, where agreements and social vigilance will limit particular interests that may destroy collective well-being, will hinder corruption and environmental destruction, and will allow actors to seriously reflect on the well-being of present and future generations (chap. 32 by Pineda/Salazar).

From this reflective and integrative standpoint, a strategic vision is outlined throughout the book that distinguishes between the structural and the contextual, where the metaphorical can generally explain strategic dynamic processes presented by the interaction between the environmental quartet, social needs, actions, and productive processes linked to water. These interactions are full of contradictions and ambiguities from both sides – the natural and the social – but nonetheless they also portray antagonisms within each field. By hoping to penetrate more deeply from the contextual to the essential, it is important to establish socially constructed and accepted hierarchies that make a common agenda possible, and where the limits[1] to water management and use are clearly stipulated; this means socially gestated pacts and concrete agreements. For this, specific legislation, norms, and procedures should be put in place and these should be constantly re-evaluated by scientific-technological and environmental knowledge (Leff, 1998, 2002) as well as by critical social participation.

34.2.3 State Regulation, Gradual and Total Deregulation of Water: Transnational Mega-Projects Versus Sustainable Facilities With Adapted Local Technology

Influenced by the 'Washington Consensus' and the spread of the neo-liberal model, Mexican authorities and business people have made 'value of change' a priority in water management. This has kept public investment from the most marginal zones in favour of the development of mega-projects. Lack of resources for these has led to public investment through external borrowing (World Bank), and this has meant servicing debt interests. In addition, the structural adjustment plans imposed by the *International Monetary Fund* (IMF) have restructured the economy and opened up water to transnational private investments. This process coincided with the creation of the *National Water Commission* (CONAGUA) in 1989, and in 1994 the *Mexican Institute of Water Technology* (IMTA) was transferred to SEMARNAT as a decentralized body. The objective of both institutions was to stimulate the efficiency of agricultural irrigation so as to provide greater coverage and quality in potable water services, sewage, and sanitation; integral water management in aquifers and basins through protection, sanitation, and conservation of water and biota; and an efficient administration with adequate tariffs that would facilitate transparent finances in the hydraulic sector. Later, from a production-oriented vision centred on virtual water (agricultural production; Allen, 2003, 2009) and administered by the Ministry of Agriculture, following the Earth Summit in Rio de Janeiro in 1992 emphasis shifted towards environmental sustainability, and SEMARNAP was charged with water management within a framework of user participation and social organization (chap. 33 by Domínguez). Taking into account the increase in frequency and degree of extreme hydrometeorological weather

1 It comes as no surprise that climate change specialists are defending a maximum temperature increase of 2°C, while most countries – including those in an accelerated development process such as Brazil, Russia, India, and China (BRIC) – are reluctant to accept limits imposed by developed countries. Given the levels of existing technological development and the costs of developing new technologies, the rapid growth model could come to a standstill.

events in the early 21st century, prevention and risk mitigation of drought and flooding were also added.

In an institutional framework with such profound changes to the *National Water Law* (LAN, in Spanish), private participation in the building of infrastructure was favoured through traditional public work contracts, concessions and services with long-term returns, and 'key in hand' concessions (this includes the building or renovating of hydraulic infrastructure by private enterprises). One of the justifications for this was the reduction of public debts, although subrogating water and sanitation services has not always proved successful; in Argentina and Peru it has generated severe conflicts and episodes of violence.

In the National Development Plan 2001–2006 and the *Programme for the Modernization of Water Operating Organizations* (PROMAGUA), BANOBRAS (FINFRA) together with loans from the World Bank and *the Inter-American Development Bank* (IDB) fostered the participation of the private sector in water services in cities with generally more than 50,000 inhabitants. This process coincided with a global policy of deregulation and privatization of public services, where the *World Environmental Centre* (WEC) in New York helped transnational enterprises decide the best investment opportunities in Mexico (Clarke/Barlow, 2004; Pinsent, 2007). Even though in 2005 the federal government – with the support of the World Bank – handed over concessions for aqueducts, wastewater treatment plants, and administrative systems in Pachuca, Aguascalientes, Saltillo, Puebla, Cancun, etc., due to substantial increases in water and sewage costs, without necessarily reflecting on improved service quality, privatization has become a politically heated topic in Mexican society.

This process of the globalization of water resources is linked with the world oligopoly of two transnational enterprises, the Compagnie Générale des Eaux currently called Vivendi, and Lyonnaise des Eaux also known as Suéz-Ondeo. Both are French in origin but they have merged with multiple smaller companies throughout the globe (Monroy, 2009; Laimé, 2003). In Mexico they are linked with power groups. It is estimated that Suéz provides water and sanitation for 7.5 million inhabitants. The structural inequality problems related to the geographical and temporal distribution of water in Mexico are not the only source of mistrust and disenchantment with these private companies (chap. 27 by Barkin). It is their voracious appetite for a quick profit by utilizing existing infrastructure and their policy of short-term investment returns that has generated scepticism and opposition among citizens (Barlow/Clarke, 2002, 2002a). Thus, conflicts over service costs have become widespread. Users claim that the state should keep control over this vital resource in order to avoid the escalation of problems as has been the case in Argentina and Peru.

No doubt, efficient administration of water is essential for maintaining and developing new water, sewage, and sanitation infrastructure (chap. 31 by Pérez). Economic theory addresses costs, benefits, crossed subsidies, tariffs, and prices. This approach has been complemented by philosophical reflections surrounding the theory of value and ethics (Scheler, 1973), where issues of equity are discussed alongside water administration; topics such as basic human rights and social and public commitments to an efficient supply of this vital liquid for all. Viewing water as a cultural good of nature that has been used over millennia as a social good with 'value of use' (Oswald, 2005), it can be concluded that each world citizen has the right to at least the minimum amount of clean water necessary for survival. This basic right was recently blocked by the transnational enterprises mentioned above in March 2009 during the fifth World Water Forum in Istanbul, Turkey, and finally granted by the General Assembly of UN in 2010.

In order to grant this right to every Mexican citizen, it is not enough to privatize water and let it be managed by transnational enterprises. Public investment should use various mechanisms to guarantee access to at least 5 litres of clean water per person per day. This minimum allowance should not be regulated by the rules of the market. Alongside water treated as a social good with 'value of use', one finds water with a 'value of change', including water for residential, industrial, and agricultural use. This can become a private good and be treated as merchandise in market terms, where the reuse of treated wastewater could also be included, e.g. in gardens and parks and for various economic activities (chap. 3 by Sánchez et al.).

In 1997 the Congress of the State of Morelos ratified a Water Tariff Law that distinguished between users and provisions for the most vulnerable groups and the environment. This law stimulated domestic water savings through a symbolic tariff for low consumption, and a progressive tariff increase for higher consumption. Productive activities paid higher prices, which also increased in proportion to their consumption levels. This allowed cross-subsidies to marginal sectors at the same time as potable water and sewage systems had sufficient resources to operate efficiently and transparently. In this process, it was crucial to have meter who quantified the users' real consumption. It was part of a strategy of fostering a wider water culture, where natural resources were valued and cared for, and where tariffs were fair according to the services provided; citizen committees monitored water administration. Overall, these strategies promoted links between civil society and public officials in order to establish the most efficient criteria for water management, regardless of whether public works were conducted by public or private enterprises (Oswald, 2005: 123–154). Above all, responsible citizen-government supervision and the protection of basic human rights were guaranteed before profits.

34.2.4 Rationale for the Water Management System: Traditional and Alternative Politics

A new water culture implies deconstructing official history and finding interests linked to water management. It also reconstructs an inclusive discourse in terms of an environmental and social discourse accountable to future generations. Given this paradigm, the book reviews the national and local history of water management in the country. Starting from a purely positivistic outlook, where water was conceived as a renewable and unlimited resource, Mexico is now faced with a different reality: water has become increasingly scarce and polluted (chap. 2 by Arreguín et al.; Biswas et al., 2006). Population has tripled and water consumption has increased sixfold worldwide. Water availability in Mexico has also been significantly reduced due to population growth, particularly in the three megacities of Mexico City, Guadalajara, and Monterrey, which are located in dry and semi-arid regions; this has led to unsustainable water needs and policies.

During the past three decades simulations with mathematical models have enabled Mexico to establish water balances and to develop future scenarios (chap. 4 by Díaz et al.) that face up to climate change and its projected impacts on the 'environmental quartet'. Optimizing water use and infrastructure as well as involving users in water management processes promotes savings and avoids pollution and waste (Arreguín/Alcocer, 2003). Seen from a systemic approach, supply and demand are closely related to economic, technological, political, social, environmental, and ideological aspects, generating participative planning in the short and long term, preserving this vital liquid for future generations without crippling present development. By using optimizing techniques complex problems may be addressed and the different aspects may be subdivided, establishing hierarchies and many levels of approximation. Existing models are a first start and they can then be linked to mathematical models and sub-systemic interactions to obtain a more integrated overall model that reflects the complexity of the water system, determining areas of flexibility and potential ruptures (Oswald, 2005).

These systemic approaches have transformed water politics. The big irrigation districts to the north in the most arid region of the country have undergone institutional and administrative changes. The Secretary of Agriculture has transferred control of water management to the Ministry of the Environment and specifically to the National Water Commission. A more integrated outlook over water management has developed that incorporates important massive engineering infrastructure projects (dams, irrigation districts, channels, levees, collectors, water treatment plants, etc). Mass deforestation and clandestine logging has led to silting in the river basins and has also affected productive and urban infrastructure; besides this, during the rainy season, they have caused floods and destruction (e.g. Tabasco). Urban planning, which had frequently been the mechanism of political clientelism, has also proved deficient, and in many mass popular settlements only territorial replanning and resettlement has saved millions from future disaster scenarios.

In this book, a crucial topic has been the water cycle, as 72 per cent (1,084 km^3) of rainfall in Mexico evaporates. Evapotranspiration directly impacts on weather conditions, purifies the air, feeds the hydrological cycle, and generates winds with solar energy; when managed through water saving and reuse technologies and within a sustainable agricultural vision, it may secure the food supply and provide agricultural producers with a fair income that matches urban incomes and consumption needs. Agriculture uses approximately 77 per cent of the water and 6.3 million hectares are irrigated (CONAGUA, 2008); urban and domestic consumption uses 13 per cent, and industry uses 10 per cent for productive activities. Table 34.1 shows the availability of surface water, also known as 'green water', essentially used in agricultural production and seldom utilized as potable water, given the high levels of pollution in rivers and the high costs of potabilization.

Ground or 'blue water' is a strategic resource for the country given its potential and quality when compared with surface water. From the 652 existing aquifers in Mexico, 104 are over-exploited and two-thirds of the water for irrigation is extracted from these

Table 34.1: Water volume in million m^3. **Source:** CONAGUA (2008).

Rainfall	1,522,000
Rivers	412,000
Dams	180,000
Lakes and lagoons	14,000

aquifers. This resource is not well managed and affects wetlands and ecosystems associated with groundwater discharges.[2] The seven most affected aquifers are located in the Valley of Mexico; this region also has the most over-exploited aquifers in the world. Sixty-seven per cent of the water supply for Mexico City is extracted from these. In December 2008 the UN found that over-exploitation in Texcoco was over 850 per cent of its average annual recharge capacity. On average, the Metropolitan Zone has an over-exploitation rate of over 200 per cent, implying a medium-term risk to water supply. This problem reflects the challenges – often associated with conflicts – in the country as a whole. In Mexico City there are 3,300 official permits but there are 6,800 wells, implying that most are clandestine. Instead of recovering these seven aquifers with sanitation technologies, water reuse, rainwater harvesting, river and rainfall infiltration, absorption wells, domestic cisterns, controlling leaks, implementing efficient measurements, imposing adequate tariffs, and cancelling clandestine wells, in 2010 a new discharge project was built to the west of the city in order to evacuate rainfall excess towards the Valley of Mezquital and avoid floods. This policy of seeking to dry out the central valley, implemented since the arrival of the Spaniards and using all the new technologies, has proved inefficient in solving flooding problems in the basin, given that the city was built over a lake. In addition to this, the present water policy has economically benefited real estate speculators.

The policy of draining the central valley is a clear reflection of the engineering paradigm; but it does not reflect integrated management of the ecosystem. If the central valley could cease extracting 15 m^3/second, subsidence could be controlled, reducing dissolution of salt and thus improving the physicochemical quality of groundwater, avoiding the formation of cavities and thus reducing the impact of tectonic movements. Mexico City has been sinking since 1925 because of this policy of water extraction (chap. 28 by Morales/Tapia). Subsidence affects the metro, the infrastructure of potable water, electricity, telecommunications, gas pipes, houses, buildings, and the international airport. Particularly noteworthy is the effect of subsidence on water quality. Today there are up to 40 centimetres of subsidence in the zones of Xochimilco and the historical centre and even more in the region of Texcoco. A paradigmatic shift in terms of integrated water management in the central valley could reverse this trend.

34.2.5 Technology, Irrigation, Pumping Systems, Irrigation Networks, Sanitation, and Water Recycling

Technology is a vital topic in sustainable water management (chap. 8 by Tapia). But technology reflecting a cornucopian vision is no panacea that will solve all problems related to water and its management. Over-exploitation of aquifers and excess use of water for irrigation and in megacities is the main focus of this book. There are still important doubts relating to water requirements per crop and climatic region. Fortunately, the National Water Law protects the most vulnerable and marginal populations in the country as well as those ecosystems that are increasingly threatened by climate change.

Efficiency in agricultural irrigation represents a technological challenge in terms of rational water use (chap. 9 by Palacios/Mejía); but there are also political and cultural aspects to offering peasants or medium-sized agricultural producers a production model that saves water and accounts for water and wind erosion, at the same time as guaranteeing the supply of strategic foods to the country at reasonable prices. An active interaction between distinct disciplines is required (chap. 11 by Muñoz et al.) in order to decide the most efficient ways to prepare furrow irrigation, sowing techniques, a germination process, micro-irrigation, micro-tunnels, drip and trickle irrigation, harvesting practices, types of crops and seeds, etc. (chap. 13 by Chávez et al.).

Mexico is located in a volcanic belt and most of its territory is exposed to tectonic movements and earthquakes. These geological processes, together with an increasing number and severity of hurricanes and more prolonged periods of drought, generate technological challenges to potable water supply systems,

2 The All-American Canal proposed by the USA in order to stop water infiltration to Mexican territory from the Colorado River will present high economic, social and environmental costs, as well as damages and costs that affect both nations, especially the fragile and biodiverse ecosystems in this arid region.

sanitation and wastewater mechanisms, water reuse for irrigation and treatment plants, and ground infiltration. Japan, a developed country also affected by recurrent tectonic movements, has implemented flexible pipe technologies that prevent leaks and ruptures during earthquakes in all of its supply system. Tokyo controls 98 per cent of its leaks in a highly unstable zone in terms of tectonic activity. Scientific-technological exchanges and adaptation of existing infrastructure to the specific conditions of Mexico with the development of our own technologies could help reduce existing giant leaks in potable water systems throughout the country.

Sanitation presents multiple technological challenges as well as threats for human and environmental health (chap. 14 by Cortés/Calderón). Toxic metals, natural organic and anthropogenic contaminants, faecal coliforms, helminths, and other hydric vectors found in ground and surface water represent a public health (chap. 16 by Avelar et al.) challenge in terms of infiltration and water reuse for productive activities, crop irrigation, and consumption. Adopting a preventive stance, Mexico could avoid multiple future problems in environmental, economic, public health, and productive fields, for example the recent case of the AH1N1 influenza pandemic. New methods and processes are being developed in public higher education institutions and associated businesses in order to confront problems preventively; these innovative technologies could be exported and successfully compete with available technologies worldwide.

Rainwater harvesting and using solar energy has been suggested in the past for isolated rural communities that lack access to public potable water supply systems (Ariyabandu/Dharmalingam, 1997). Nevertheless, rainwater harvesting goes back centuries in Mexico; most archaeological excavations show evidence of careful water management in indigenous societies. Trees retain water: between 10 and 20 per cent of water run-off is slow and gradually percolates through fallen leaves and infiltrates into the subsoil. In arid regions there are different mechanisms that plants use to retain water. Based on this, many different technologies have been developed in order to retain rainwater in ferro-cement tanks, cisterns, and containers or in small dams in river beds and creeks as well as in bigger multipurpose dams (electricity, irrigation, control of water level). However, the term rainwater harvesting is normally used to refer to the retention of rainwater in smaller units for storing water to be used in times of drought (chap. 26 by González/Galván).

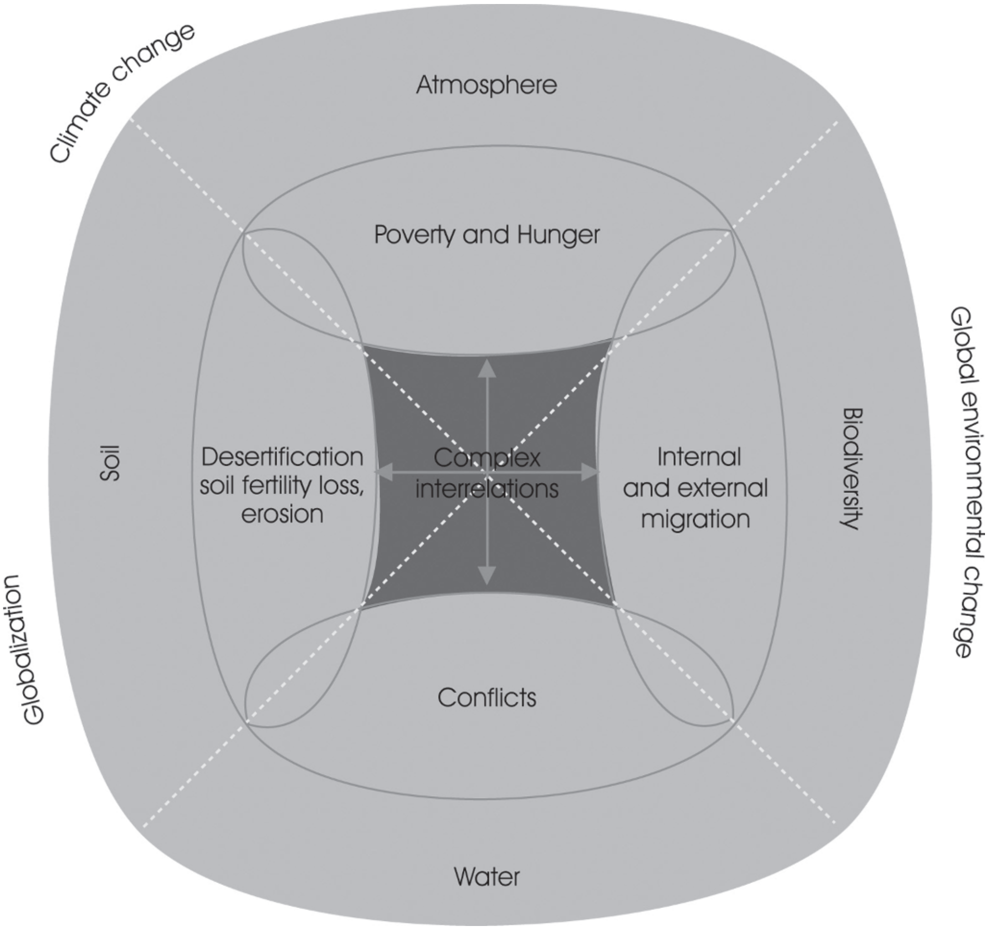
In order to make water management efficient in the hope of consolidating a water culture, it is important to develop legal mechanisms and norms that stimulate rainwater harvesting and foster local public works for retaining and storing rainwater (e.g. also cenotes; chap. 18 by Pacheco et al.). This can be achieved through construction regulations, where builders are obliged to install cisterns for storing rainwater, and to separate black from grey discharge waters, recycling the latter in gardens, parks, toilets, etc. There are also geomembranes that can retain greater amounts of water in permeable areas of the subsoil destined for collective use. This is especially useful in areas where it is not possible to dig potable water supply wells. Another method is building individual ferro-cement tanks in houses to store rainwater. These processes may thus foster a water culture that encourages water saving and makes urban dwellers understand the importance of water and water supplies in densely populated areas and arid climate regions with over-exploited aquifers. Integrated water management can also include solar heaters and energy savings in order to improve all natural processes without affecting the quality of life of human populations.

34.2.6 Interaction Between Water Agents, Governance, Integral Management and Politics: From Water Politics to an Integrated Basin Management

Water as a vital liquid is part of all the processes of daily life; from productive to recreational and cultural processes. Conflicting interests in water use demand legislation to foster social participation and prevent conflict. The *National Water Law* (NWL; in Spanish LAN) establishes water use priorities, including not only human needs and socio-economic processes, but also nature as a key user of the vital liquid (chap. 33 by Domínguez) and provider of environmental services. Despite these legal advances, the NWL and its norms still lack an innovative approach that will care for water in environmental and productive processes, and human use as well as clean wastewaters through treatment plants at the end of the pipe. Prevention and early warning systems can avoid human losses (chap. 19 by Mathuriau et al.) and damage to costly infrastructure in the face of hydrometeorological events, at the same time as water conservation and transformation of productive processes lessen surface, ground, and sea water pollution.

A second area of opportunity is linked to water administration. In the 1990s, Mexico has seen the

Figure 34.2: Complex interrelations between water, society, and nature. **Source:** Developed and designed by the author.



decentralization of water resources from a previously firmly centralized system. State and municipal governments now administer *Potable Water and Sanitation Systems* (PWSS). A transparent administration, with socially agreed water tariffs and subsidies that stimulate creativity, innovation, saving, and reuse of water are vital because of increasing pollution and scarcity (chap. 30 by Martín et al.). The present model privileges minority sectors, granting them a hydraulic productive infrastructure at the expense of other sectors, and it is not sustainable in the long run as it generates conflict and violent confrontations at local level (UNESCO, 2006).

A new water culture requires active social participation going beyond written norms and goodwill; it needs to transform everyday assumptions and people's relationship to water, avoiding conflicts and preserving the vital liquid for future generations (figure 34.2). Optimizing the use of a scarce resource also requires looking at ways in which humans interact with water (chap. 25 by Galván) and with the environment in a wider sense (Brauch et al., 2009). Natural resources are not only there to satisfy basic needs, but also enable humans to profit from the beauties of nature, where the most profound and sacred aspects of water can be found and can be translated to the cosmovision of human groups. Also, a different water culture helps to make people aware of the importance of water for the development and the conservation of nature. Raising awareness of good use and preservation of water requires educational activities that contribute to sanitary prevention and reduction of waterborne diseases. Overall, this calls for changes in underlying attitudes and behaviours. Up until recently, water was seen as indestructible and inexhaustible. Only recently have cholera and interrupted water supplies in cities raised awareness of the need to develop attitudes that care for and preserve water and value all the benefits it brings for societies (chap. 17 by Arreola). Only very recently has a commitment to pay for water services developed at the local level.

This new water culture has transformed lifestyles characterized by production of wastewater towards a culture of sustainability. Models of social participation, regulation (chap. 29 by González/Zamora) of and by the authorities, long-term services and so on have developed that account for both ground and surface waters, given that most water destined for human consumption in Mexico is extracted from aquifers. Over-exploitation of aquifers has also generated models of integrated water management in order to guarantee long-term water availability (chap. 5 by Medina et al.), including a rigorous administration and management coupled with conflict prevention and mitigation, as well as an emphasis on water governance.

The notion of water governance has risen above the administrative-financial outlook and has been linked to wider political topics such as the basic human right to clean water, democracy, justice, and social participation; in brief, to human and global environmental security (Brauch, 2009, 2009a; Oswald/Brauch, 2009). Sustainability, too, has been increasingly incorporated into the notion of water governance, in such a way that this notion now goes beyond management, operation, and maintenance of water infrastructure, to become the analysis of the complex interrelationship between the social and environmental quartets (figure 34.2). In this sense, it also helps to ease tensions that have been generated by water scarcity and pollution (chap. 15 by Hansen/Corzo), as well as by the unequal distribution of water resources. Hence, water governance investigates the technical, environmental, and social viability of reforms to public policies concerning water and its associated services.

This integral socio-environmental outlook demands a new water policy, one where society, government, and businesses take on integrated water management. It starts in the upper basin, and accounts for environmental services generated in the mountains that go beyond dams and the extraction of timber (chap. 11 by Muñoz et al.). Specifically, integrated basin management reverses the model of exploitation and destruction and transforms it to long-term conservation. However, it applies not only to the higher basin, but also to the middle and lower basin, to processes of territorial and environmental planning, and to shifting processes of urbanization, so as to lead towards sustainable management of all existing natural resources. This includes agricultural management and aquaculture as additional sources of food for a growing population, without destroying the most vital resources necessary to attain quality of life, health, and well-being for groups of humans and for nature (chap. 10 by Peña).

34.2.7 Future Perspectives: A Cross-Sectional Water Vision for Mexico's Development

One of the main goals of the *Scientific Network on Water* (RETAC) at this early stage has been to find complex interrelated and interdisciplinary topics that present deficiencies and that have research potential, where research teams from different backgrounds with complementary methodologies can provide a fresh and integrated outlook on water management for the country. During the First Meeting in Cocoyoc, complemented with the Second International Congress in Cuernavaca in 2010, multidisciplinary reflections were put forward and summarized in the present conclusions. They are grouped around seven overarching thematic axes: ground and surface water pollution and scarcity and its repercussions in health and nature (chap. 16 by Avelar et al.); physical and economic water stress and how it may be overcome through efficient administration, technologies, and adequate tariffs; the complex and chaotic interrelationship between the 'environmental' and 'social quartets'; water scarcity and pollution aggravated by population growth, productive processes (chap. 20 by De la Garza/Herrera), and urban and rural development requiring territorial and environmental planning for the basin; water, soil, agricultural production, foodstuffs, hunger, and the attainment of food security; complex solutions in the face of the effects of climate change and lack of survival conditions given forced migration, conflict and hunger; and the negotiation of sustainable development with sustainable peace, hydrodiplomacy, economic tools and an integrated water culture.

a) There is no doubt that ground and surface water pollution from viruses, bacteria, fungi, agrochemicals, industrial toxins, and natural waste affects biodiversity and aquatic life in the water basins, but it also damages human health and the ecosystem, affecting its capacity to self-regulate and recuperate. Because of changes in the range of industrial and agricultural products (chap. 19 by Mathuriau et al.), often with a higher toxicity[3] and more complex interactions with the environment, it is important to understand the threshold of responsiveness of species and ecosystems that are affected by pollution. Tests must be developed to prevent any harmful effects of these products on human health, including chronic and degenerative illnesses and widespread deaths, as well as to protect and preserve ecosystems and development (chap. 21 by Vallejo/López). In this way, epidemiology is linked to these practices and to environmental exposure, where policies of prevention of damage to human health and the ecosystem may be consolidated as part of a wider culture of prevention and conservation.

It is essential to develop simple diagnostic methods at adequate cost to prevent greater and irreversible damage and pollution and destruction of the vital liquid. Here we would include potable and recycled water indicators to prevent damage in the immune system as well as mutagenic and chronic illnesses that impair vital organs. Finally, it is much cheaper to prevent pollution and transform the current policy of sanitation 'at the end of the pipe' for preventive activities and changes to productive processes.

It is also important to modify policies that make it cheaper for businesses to pay environmental fines rather than restructure or reduce their polluting productive processes, where the higher cost is paid by society (chap. 22 by González/Escamilla). Environmental regulations should not be crippled by short-term political or economic interests such as immediate electoral popularity. Instead, linking private investment to environmental research and preservation could open new market niches, generate sources of employment, and at the same time contribute towards the sustainable development of the country, recuperating its natural and human capital through indigenous and modern technologies.

b) The second topic is water scarcity caused by lack of water availability or economic stress that leads to an inadequate water service and infrastructure. Changes in hydrological patterns and in the ecosystem generate new risks and vulnerabilities in the face of more extreme hydrometeorological events caused by climate change. Without a culture of prevention, characterized by systematic monitoring systems, accurate forecasts (chap. 8 by Tapia), prevention plans, and programmes of mitigation and adaptation, integrated sustainable management will not be possible. This calls for an appropriate regulatory framework with permanent monitoring and updating, where urban and rural development, health hazards, and survival are accounted for by bioindicators and integrated development models. These should include not only massive infrastructure works but also micro and mid-range works and businesses that will enable society to be trained and organized so that a more harmonious relationship can exist between nature and productive processes.

Thus, the economy, public and private investments, tariffs, economic gains and losses, honest and efficient administration of potable water, and sewage and sanitation systems with water reuse and recycling are combined with low-cost technologies that can be managed by trained technicians in the longer run. Here, environmental externalities should be accounted for, as well as water saving and sanitation investments, fiscal incentives to promote new technologies and their maintenance, use of renewable technologies and potabilization plants, pumping, wastewater treatment, and payment for environmental services. If civil society is not organized, these political changes and investments will not be possible and quality of life will not be guaranteed for all the inhabitants of the Mexican territory, since social, seasonal, and regional inequalities in terms of water access will not be overcome.

In addition, there are investment proposals by international organizations that do not reflect the reality of the country. Frequently, they represent an interest in transnational privatization and in massive public works, when what Mexico requires is adapted, less costly technologies that can more easily be assimilated by all users. Through education and the development of a new environmental culture, factional political interests may be overcome. Finally, existing laws need to be amended in order to reflect the real water situation in the country. Regulation manuals for efficient use of water need to be implemented in irrigation districts as there are currently none and this sector is the main consumer of water in dry and semi-arid regions (chap. 4 by Díaz et al.). If users learnt the advantages of accessing fully potable water, without leaks, and become part of the decision-making process with truthful and transparent information, consumers would change their attitude; not only would a new water culture ensue, but users would

3 Given the tremendous growth in the production of industrial toxic compounds, illustrated by the introduction of between 200 and 1,000 new compounds annually (Moriarty, 1988), it is necessary and urgent to develop tests that provide safe and scientifically sound results that can be used in legal disputes regarding accountability for damage to human beings and ecosystems.

also participate with timely and fair payments for water services and for the modernization and maintenance of the water infrastructure.

c) Undoubtedly, there is a complex interrelationship between the 'environmental quartet' – weather, soil, water, and ecosystems – and the effects of climate change: the increasing number of and the more intense nature of hydrometeorological disasters, as well as adaptation, mitigation, and resilience processes, both from ecosystems and societies. Mexico is severely exposed to desertification and land degradation, but also to drought and flash floods (Rosenfeld/Rudich/Lahav, 2001)[4]. Climate change and human activities cause further stress on drylands – which represent 58 per cent of Mexico's land area – affecting semi-arid, arid and hyper-arid regions (deserts) that are currently facing a severe process of deterioration (SEMARNAT, 2006).

   Prolonged and more intense droughts and erratic and more localized precipitation becoming more intense in the short term have led to greater water erosion at the same time as a lack of rainfall has led to wind erosion. These climatic changes have affected ground cover and facilitated the development of new plagues and plant and animal illnesses. Also, since ecosystems only adapt to sudden changes gradually, biodiversity in Mexico is threatened. Mexico is the fourth country in terms of biodiversity worldwide, offering multiple global environmental services that are seldom accounted for or protected by socio-economic compensation. However, these services will become increasingly important in the future.

   Thus, it is imperative to guarantee ecological streams to the ecosystems under stress, limiting the over-exploitation of water and other resources through the four R's (RRRR: *reducing, recycling, reusing, and re-educating*). When water in an ecosystem is exploited beyond its resilience capacity, it is destroyed. On the other hand, when an ecological stream is guaranteed through integrated water management, the landscape, the surrounding environment and environmental services are also restored. This calls for scientific methodologies where knowledge and methods are transferred to users and to the public sector, and where legislation and public policies reinforce a harmonious relationship between the social and environmental quartets. It is a particular challenge to restore these processes in big cities, where only rigorous urban planning in harmony with the ecosystem may improve the quality of life for urban inhabitants, once a participative administration model has been implemented and natural services and benefits are valued.

d) Equally important is the interrelationship of water with the 'social quartet', where population growth and socio-economic and cultural processes such as rural development and urbanization on a global scale have led to scarcity, pollution, and destruction. Besides this, new hygiene requirements and productive processes put pressure on the availability of water. Inequalities in this process are reflected in a regressive globalization (Brauch et al., 2008; Held/McGrew, 2007; Held et al., 1999; Oswald, 2009; Oswald/Brauch, 2009, 2011) where the core goal is profit maximization at any cost. This outlook has important repercussions in nature and also has severe social effects, as can be seen in the global economic crisis since 1998 and in the cascading disaster effects triggered by the earthquake-tsunami in Japan in March 2011 resulting in radiation from damaged nuclear plants affecting water, soil, food, health and livelihood security. As well as this, hydrometeorological disasters (Magaña/Méndez/Millán, 2004; Magaña 1999) severely affect the most vulnerable social sectors, especially women, who risk their lives not only in Mexico but in the entire world to save others, through their social representation and socialized identity as carers (Birkman/Nishara/Hettige, 2006; Villagran, 2006; Oswald, 2008; Ariyabandu/Fonseka, 2009).

   All this is also reflected in the processes of poverty increase, hunger, and misery (CEPAL, 2008; Oswald/Brauch, 2009; FAO, 2009; Ziegler/Kalbermatten, 2008). Food shortages and dependency on basic food prices set by the international market, speculative practices relating to financial capital, monopolies, and oligopolies have all generated the greatest food crises. Mexico is not exempt from this problem, since in January 2007 the crisis in tortilla prices showed that prices do

4 The process of desertification and land degradation is accompanied by a loss of natural soil fertility and erosion is severe in Mexico. According to SEMARNAT (2006), 93 million hectares or 47 per cent of national territory shows signs of desertification processes. According to Riod.MEx (2008), this process has already affected 120 million hectares, 93 per cent of which as a result of poor soil management. The main causes are fertility loss (18 per cent); water erosion (12 per cent), wind erosion (11 per cent), and salinization (8 per cent).

not depend only on physical soil conditions, plagues, and water availability. In this particular case, it was speculation in basic foodstuffs, massive use of corn for biofuel in the USA and price increases that caused three million more poor people in Mexico, of whom two million face food poverty or hunger (INEGI, 2009).

Water availability studies, quantification of ecological damage, development of conservation methods and techniques, and water reuse and recycling from integrated studies at the basin level would enable the existing legal framework to be adjusted to overcome the deficiencies of the National Water Law. This would need management of groundwater to be integrated with that of surface water, revision of previously granted official water extraction permits, and assessment of the damage caused by changes in the natural hydrological patterns, for example changing river courses. An environmental reordering involves regional diagnoses, where the real costs of water extraction, potabilization, discharges, sanitation, and reposition are calculated in order to keep a balance in the 'environmental quartet'.

e) Given adverse climatic conditions, agricultural producers use around 77 per cent of available water for food production. Food is considered as 'virtual water' (Allen, 2003) due to the significant amounts of water that is needed for its production. It is precisely in the most arid regions of the planet where the most acute problems of hunger exist. In these regions, irrigation has been used to compensate for irregular or absent rainfall. However, because of irrigation, groundwater quality has been affected and groundwater now has greater levels of dissolved salts (chap. 6 by Perry et al.), which leads to the salinization of agricultural soils, further aggravated by sea water intrusion into groundwater (chap. 5 by Medina et al.). This is the result of poor irrigation management, low efficiency, and over-exploitation of aquifers through the proliferating number of wells dug at greater depths, where water with high salt and mineral content is extracted. Thus, excess water use cannot only be attributed to climate change; human behaviour is the main cause of poor water quality and scarcity.

As well as this, there is a lack of knowledge about the exact requirements of water for each crop, about the most efficient tools for irrigation, about suitable technological developments that fit the culture of the users, and about the perverse effects of subsidies for energy, diesel, and irrigation costs, which stimulate waste, cause damage to large infrastructure works, and lead to a lack of alternatives for small and subsistence producers who cannot afford costly technologies or do not get subsidies.

In addition, this field lacks research and investment linked to producers, where government officials at each level and producers get together on a single project, where they can stimulate each other and seek socially and technically acceptable solutions to the water situation in semi-arid and arid regions for the common good. Over-exploitation of aquifers, soil pollution, and poor water quality can only be overcome in such a way. This requires using productive processes more suitable for changing weather and soil conditions. Thus, it is important to quantify and fix a price for the environmental externalities generated by commercial agriculture, presently paid for by Mexican society through taxation or through health problems, while a small group of export-oriented agribusinesses reap the benefits.

The proposals by FAO and the World Bank should be taken seriously in agricultural processes, and environmental services provided by peasants located in the higher basin should be taken into consideration. Usually, many of these peasants live in highly marginal conditions and their environmental services are taken for granted while the urban and agro-productive sectors in the lower basin benefit from the implicit subsidies for these services. Given these more adverse socio-environmental conditions, poor and indigenous peasants working in these marginal sectors often face a survival dilemma (Brauch, 2009) and are often forced to migrate and to abandon their lands or to stop providing these necessary environmental services, for example due to climate change.

f) With all these factors, we can see a complex interrelationship between the factors comprising the 'environmental' and 'social quartet' referred to in the PEISOR model (Oswald/Sánchez, chap. 1 above; Brauch 2009a, Brauch/Oswald 2009). So far, there is little rigorous research that analyses the complex links and the interrelationships between the natural environment and social elements in an integrated and serious way (figure 34.2). Both hunger and mass migration to shanty towns in big cities or to foreign countries (PEW Hispanic Center, 2009) can hide more extreme and adverse conditions in their local and regional setting, for example access to increasingly scarce resources. This situation can become unmanageable if severe environmental disasters, economic crises, massive employment losses, high inflation, public insecurity, lack of governance, people trafficking, drugs, and guns lead to survival dilemmas (Brauch, 2009; Oswald Spring, 2001, 2011). In these situations of high complexity, traditional bonds of social cohesion may fracture, leading to local violence and regional wars, displacements, and refugees (Homer-Dixon/Blitt, 1999; Homer-Dixon, 1991, 1994, 1999, 2000). Extreme emergencies, where a natural hazard impacts on a violent conflict, have occurred in the past. The Darfur case is among the best-known ongoing conflicts. In order to avoid these, it is important to initiate preventive mechanisms for conflict mitigation and resolution, before complex emergencies escalate to become regional wars and where the people most affected lose their livelihood and possessions.

g) To avoid these extreme situations, water should become an element of peace and not of conflict, where hydrodiplomacy (Oswald, 2005, 2007 and chapter 23) may bring the three key actors together in a joint project. The state, the economy, and society (Weber, 1987) may jointly develop adaptation, mitigation, and alternative mechanisms in order to face extreme crisis situations and avoid violence. This signals the need to develop productive processes that generate quality of life for all citizens (Oswald 2009, 2008a). The private sector should contribute to this agenda, investing in projects that stimulate technological development in Mexico, generate employment, and fully use the innovation and development potential of its people, instead of allowing it to remain a backward country of cheap labour and maquila.

There is great creative potential for innovation but it is currently underutilized due to a lack of private and public resources. It could offer cross-sectional alternatives and technological developments (chap. 20 by De la Garza/Herrera; chap. 21 Vallejo/López and chap. 22 González/Escamilla) for efficient water management, including social and environmental aspects and their complex interrelationship. No country can develop and consolidate the quality of life of its citizens without managing water and energy efficiently. Instead of massive public works such as dams that displace millions of native inhabitants and destroy the environment, the potential of micro water works (e.g. water peak suppression, small reservoirs, water harvesting) may help mitigate the effects of climate change, generating development through micro and medium-sized businesses in rural areas and in higher basins with an important economic impact on marginal regions. Such projects should be stimulated by laws and policies of innovation that will reduce regional disparities and overcome the marginalization that affects more than half of the Mexican population.

In synthesis, the complex interrelationship between the social and environmental quartet represent risks and dangers for nature and for society as a whole (Beck, 2001, 2011), even if they open up opportunities for overcoming historical obstacles. In order to face the challenges of climate change, Mexico could shift towards a path of sustainable development with equity, benefiting all its citizens. In this way, the country could comply with the water security postulates (Oswald/Brauch, 2009b) defined by the Ministerial Declaration of The Hague on "Water Security in the 21st Century" (World Water Forum, 2000) that was adopted at the Second World Water Forum in 2000, namely: "ensuring freshwater, coastal, and related ecosystems are protected and improved; that sustainable development and political stability are promoted; that every person has access to enough safe water at an affordable cost to lead a healthy and productive life; and that the vulnerable are protected from the risks of water-related hazards". [5]

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Abbreviations

A(wz) warm sub- humid
AC activated carbon
Acm mildly warm and humid
ADF Augmented Dickey-Fuller
AH1N1 influenza pandemic of swine flue
Am warm humid
AMIFAC Asociación Mexicana de la Industria Fitosanitaria (Mexican Phytosanitary Industry Association)
AML allowed maximum limits
ANEAS Asociación Nacional de Empresas de Agua y Saneamiento (National Association of Water and Sanitation Utilities)
ANOVA Analysis of variance
ANUR Asociación Nacional de Usuarios de Riego (National Association of Irrigation Users)
AOP advanced oxidation processes
AOP-O_3 advanced oxidation processes that use ozone
APAZU Programa de Agua Potable, Alcantarillado y Saneamiento en Zonas Urbanas (Program for Piped Water, Sewage and Sanitation in Urban Zones)
AQDS anthraquinone 2,6-disulfonate
ASFA Abstracts for Biological Sciences, Aquatic Sciences and Fisheries
ATSDR Agency for Toxic Substances and Disease Registry, USA
AUSRIVAS Australian River Assessment Scheme
AVHRR Advanced Very High Resolution Radiometer
AW autumn–winter
AWS automatic weather stations
AWWA American Water Works Association

BANOBRAS Banco Nacional de Obras y Servicios Públicos (National Bank of Public Works and Services)
BBI Beck´s Biotic Index
BCI Biotic Condition Index
BIC Bayesian Information Criterion
BID Banco Interamericano de Desarrollo (Inter-American Development Bank)
BMWP Biological Monitoring Working Party
BOD biochemical oxygen demand
BOT build, operate and transfer
BREB Bowen Ratio Energy Balance
BRIC Brazil, Russia, India and China
BTEX benzene, toluen, ethylbenzene, xylenes

C_0 initial dye concentration
CAEV Comisión del Agua del Estado de Veracruz (Water Commission in the State of Veracruz)
CAFOs Concentrated Animal Feeding Operations
CC climate change
cc correlation coefficient
CCME Canadian Council of Ministers of the Environment
CE volume of flow
CENAPRED Centro Nacional de Prevención de Desastres (National Disaster Prevention Centre)
CENICA-INE Centro Nacional de Investigación y Capacitación Ambiental del Instituto Nacional de Ecología (National Environmental Research and Training Centre; National Institute of Ecology)
CENID RASPA (INIFAP) Centro Nacional de Investigación Disciplinaria en Relación con Agua, Suelo, Planta, Atmósfera (National Centre for Disciplinary Research on Water, Soil, Plants and Atmosphere Relations) of INIFAP
CEPAL Comisión Económica para América Latina y el Caribe (Economic Commission for Latin America and the Caribbean)
CEPIS Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente (Pan-American Center for Sanitary Engineering and Environmental Sciences)
CESBIO Centre d'Etudes Spatiales de la BIOsphère (Center for the Study of the Biosphere from Space)
CFE Comisión Federal de Electricidad (Federal Commission for Electricity)
CG chromatography of gases
CH Costa de Hermosillo (Coast of Hermosillo)
CIAD Centro de Investigación en Alimentos y Desarrollo (The Research Centre for Food and Development)
CIATEC Centro de Investigación Aplicada en Tecnologías Competitivas (The Center of Applied Innovation in Competitive Technologies)
CILA Comisión Internacional de Límites y Agua (International Boundary and Water Commission)
CINVESTAV Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (Research and Advanced Studies Centre of the National Polytechnic Institute of Mexico)
CKD Chronic Kidney Disease
CL chromatography of liquids
CNES Centre National d'Etudes Spatiales (National Centre for Space Studies)
COD chemical oxygen demand

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COFEPRIS Comisión Federal para la Protección contra Riesgos Sanitarios (Federal Commission for Protection against Health Risks)
COLPOS Colegio de Posgraduado (College of Postgraduates. Teaching and Research Institution in Agricultural and Livestock Sciences)
COMDA Coalición de Organizaciones Mexicanas para el Derecho al Agua (Coalition of Mexican Organizations for the Right to Water)
COMIMSA Corporación Mexicana de Investigación en Materiales (Mexican Coporation for Research on Materials)
CONACYT Consejo Nacional de Ciencia y Tecnología (National Council on Science and Technology)
CONAFOR Comisión Nacional Forestal (National Forestry Commission)
CONAGUA Comisión Nacional del Agua (National Water Commission)
CONAPO Consejo Nacional de Población (National Population Council)
CORENA Comisión de Recursos Naturales, México D.F. (Natural Resources Commission, Mexico City)
CP Colegio de Posgraduados (see COLPOS)
CPC Climate Prediction Center
CSVA Consejo del Sistema de Agua Veracruzano (Water System Council in the State of Veracruz)
CUEAE-SDGIH Coordinación del Uso Eficiente del Agua y Energía Eléctrica (Coordination of Efficient Water and Electric Energy Use)
CZVM Conurbation Zone of the Valley of Mexico

D&F dioxins and furans
DBF DBF, computer programme
DDR districts of rural development
DDT dichloro-diphenyl-trichloroethane
DEHP hexachlorocyclohexane, lindane, bis(2-ethylhexyl)phthalate
DEM Digital Elevation Model
DGGIMAR Dirección General de Gestión Integral de Materiales y Actividades Riesgosas (General Directorate for Integrated Management of Risky/Hazardous Materials and Dangerous Activities of SEMARNAT)
DLDD desertification, land degradation, and drought
DVI normalized difference vegetation index

EAP economically active population
EC eddy covariance
EC electrical conductivity
ECOS-Nord Evaluación, Cooperación, Orientaciones Científicas (Scientific Cooperation Programme, France)
ECs emerging contaminants
EDC endocrine disrupting compounds
EH inhibitors of cholesterol biosynthesis
ELISA batteries of biochemical tests and serologic confirmation
EMA Entidad Mexicana de Acreditación (Mexican Accreditation Body)
EMA Environmental Monitoring and Assessment
ENIGH Encuesta Nacional de Ingresos y Gastos de los Hogares (National Survey of Household Income and Expenditure)
ENSO El Niño Southern Oscillation
EOF Empirical Orthogonal Function
EOS Earth Observation Satellites
EPA Environment Protection Agency
ET evapotranspiration

FAO Food and Agriculture Organization of the United Nations
FBI Family Biotic Index
FINFRA Fondo de Inversión de Infraestructura del Gobierno Federal (BANOBRAS) (National Infrastructure Fund of the Federal Government, BANOBRAS)
FIRA Fidecomisos Instituidos en Relación con la Agricultura (Trust Funds for Agricultural Development)
FIRIOB Fideicomiso del Sistema de Aguas Residuales del Alto Río Blanco (Trusteeship for Water Sewage Systems in the Upper Blanco River)
FIs flexible incentives
FONDEN Fondo de Desastres Naturales (National Fund for Natural Disasters)
FORMOSAT Taiwanese programme of earth observation satellites
FPRWR Federal Public Register of Water Rights

GC gas chromatography
GDP gross domestic product
GFAAS graphite furnace atomic absorption spectrometry
GHG greenhouse gases
GIRH Gestión Integrada de Recursos Hídricos (Integrated Water Resources Management)
GIS Geographic Information Systems
GMD Grupo Mexicano de Desarrollo (Mexican Development Group)
GOES Geostationary Operational Environmental Satellites
GTP groundwater treatment plant
GUZ Guadalajara Urban Zone
GWP Global Water Partnership

HAR Hydrological-Administrative Region
HPA polycyclic aromatic hydrocarbons
HQ hazard quotient

IAP Immediate Action Plan
IBB Belgian Biotic Index
IBI indices of biotic integrity
IBQG General Biological Quality Index

IBWC	International Boundary and Water Commission
ICA	International Cartography Association
ICAV	Índice de Calidad Ambiental Visual (visual environmental quality index)
ICLW	International Commission of Limits and Water
IDB	Inter-American Development Bank (BID above)
IDW	inverse distance weighting
IIBACA	coleopteran-based IBI
IIBAMA	biotic integrity indices (macroinvertebrates)
IIMI	International Irrigation Management Institute
IKONOS	IKONOS Satellite sensor
IMAE	Instituto del Medio Ambiente del Estado de Aguascalientes (Institute of the Environment, State of Aguascalientes)
IMSS	Instituto Mexicano del Seguro Social (Mexican Social Security Institute)
IMTA	Instituto Mexicano de Tecnología de Agua (Mexican Institute of Water Technology)
INAGUA	Ingeniería de Agua, San Luis Potosí (Water Institute, State of San Luis Potosi)
INE	Instituto Nacional de Ecología (National Institute of Ecology)
INEGI	Instituto Nacional de Estadísticas y Geografía e Informática (National Institute for Statistics and Geography)
INIFAP	Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (National Forestry, Agriculture and Livestock Research Institute)
INSP	Instituto Nacional de Salud Pública (National Institute of Public Health)
InterAgBar	Corporativo de Barcelona en Agua y Ambiente (Holding relating to water, health and, environment based in Barcelona)
IPN	Instituto Politécnico Nacional (National Polytechnic Institute)
IPRN	Instituto Peruano de Recursos Naturales (Peruvian Institute of Natural Resources)
IPTRID	International Programme for Technology and Research in Irrigation and Drainage
IRD	Institut de Recherche du Développement (Research Institute on Development)
ISIS	Integrado de Sistemas de Información, programa de computación (computer programme)
ITSON	Instituto Tecnológico de Sonora (Sonora Institute of Technology)
Kc	crop factors
LAN	Ley de Aguas Nacionales (Mexican National Water Law)
LANDSAT	Satellite for Ecosystem Science and Technology Branch
LC	liquid chromatography
LST	low surface temperature
LTHE	Laboratoire d'Étude de Transferts en Hydrologie et Environnement, Grenoble France (Laboratory of Environmental Hydrology and the Study of Transfer Processes, Grenoble, France)
m.t	million tons
MA	Millennium Ecosystem Assessment
MADL	Maximum Allowable Daily Level
MAL	Maximum allowed limits
MAVM	Metropolitan Area of the Valley of Mexico
MBAS	methylene blue active substances
MDGs	Millennium Development Goals
MDN	Mercury Deposition Network
meq/kg	milliequivalent/kilogramme
METRIC	Mapping Evapotranspiration at High Resolution with Internalized Calibration
MLE	maximum likelihood estimation
MODIS	Moderate Resolution Imaging Spectroradiometer
MS	mass spectrometry
MWh	mega watt hour
MWTP	municipal wastewater treatment plants
MZMC	Metropolitan Zone of Mexico City
MZVM	Metropolitan Zone of the Valley of Mexico
NACEC	North American Commission for Environmental Cooperation
NADP	National Atmospheric Deposition Programme
NAFTA	North American Free Trade Agreement
NARAP	North American Regional Action Plans
NCW	New Water Culture
NDVI	high vegetation index
NDWI	Normalized Difference Water Index
NGO	Nongovernmental organization
NIR	near infrared
NIST	National Institute of Standards and Technology (USA)
NIU	Northern Illinois University
NOAA	US National Oceanic and Atmospheric Administration
NOM	Norma Oficial Mexicana (Official Mexican Standard)
NPPF	'non-point production function'
NPS	non-point Source
NRC	National Research Council (USA)
NV/AMP	curve against time (decay curve)
NWL	National Water Law
OC	organic charge
OCPs	organochlorinated pesticides
OECD	Organization for Economic Co-operation and Development
OECD/ SOPEMI	Organization for Economic Cooperation and Development/ Working Group on Migration

ORSTOM	Office de la Recherche Scientifique et Technique d'Outre-Mer (Research Office on Science and Technology in Developing Countries)
PAH	polyaromatic hydrocarbon
PAHs	polycyclic aromatic hydrocarbons
PAL	Clean Water Programme
PAN	panchromatic broad band
PAN	Partido de Acción Nacional (National Action Party, Mexico)
PAOs	processes of advanced oxidation
PBTS	persistent bioaccumulative toxic substances
PCA	principal component analysis
PCB	polychlorinated biphenyls
PCR	polymerase chain reaction
PES	Payments for Environmental Services
PLANAME	Plan Nacional de Monitoreo y Evaluación Ambiental (National Environmental Monitoring and Evaluation Plan; see also DGGIMAR)
PM	molecular weight
PNH	Programa Nacional Hídrico (National Water Resources Program, Mexico)
POPs	Persistent Organic Pollutants
PPD	purified protein derivative
ppm	parts per million
PRD	Partido de la Revolución Democrática (Democratic Revolutionary Party, Mexico)
PRI	Partido de la Revolución Institucional (Institutional Revolutionary Party, Mexico)
Procampo	Programa de Apoyos Directos al Campo (Mexican Agricultural Support Program)
PROFEPA	Procuraduría Federal de Protección Ambiental (Attorney General's Office for Environmental Protection)
PROMAGUA	Programa para la Modernización de Organismos Operadores (Water Utility Modernization Project)
PRONAME	Programa Nacional de Monitoreo y Evaluación de Sustancias Tóxicas, Persistentes y Bioacumulables (National Plan of Environmental Monitoring and Evaluation of Persistent Toxic Substances)
PLANAME	Plan Nacional de Monitoreo y Evaluación de Sustancias Tóxicas, Persistentes y Bioacumulables (National Environmental Monitoring and Evaluation Plan)
PROSSAPYS	Programa para la Construcción y Rehabilitación de Sistemas de Agua Potable y Saneamiento en Zonas Rurales (Drinking Water Supply and Sanitation Sustainability Program)
PS	point source
PUEC	Programa Universitario de Estudios sobre la Ciudad (University Programme of Urban Studies, UNAM)
PVC	plicloruro de vinilo (polyvynil chloride)
R	removal rate
RAKKSS	Evaluación Rápida de los Sistemas de Reconocimiento Agrícola (Rapid Assessment Methodology for Systems of Agricultural Recognition)
RC	runoff coefficient
REDALYC	Red de Revistas Científicas de América Latina y El Caribe, España y Portugal (Network of Scientific Journals from Latin America, the Caribbean, Spain and Portugal)
RETAC	Red Temática del Agua, CONACYT (Scientific Network on Water, National Council on Science and Technology, Mexico)
RIOD-Mex	Red Mexicana de Esfuerzos contra la Desertificación y la Degradación de los Recursos Naturales (National Network of Efforts against Desertification and Degradation of Natural Resources)
RIVPACS	river invertebrate prediction and classification system
RNM	Red Nacional de Monitoreo (National Monitoring Network)
RRP1	degradation route
RRRR	reduction, recycling, reuse and re-education
SACM	Sistema de Aguas de la Ciudad de México (Municipal Water Utility of Mexico City)
SAGAR	Secretaría de Agricultura, Ganadería y Desarrollo Rural (Ministry of Agriculture, Livestock and Rural Development)
SAGARPA	Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (Mexican Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food)
SARH	Secretaría de Agricultura y Recursos Hidráulicos (Mexican Ministry of Agriculture and Water Resources)
SAVI	Soil Adjusted Vegetation Index
SCI	Sequential Comparison Index
SD	sustainable development
SDGIH	Subdirección General de Infraestructura Hidroagrícola (Department of Irrigation Districts)
SEBAL	Surface Energy Balance Algorithm for Land
SEC	Secretaría de Economía (Mexican Secretary of Economy)
SEDESOL	Secretaría de Desarrollo Social (Mexican Ministry of Social Development)
SEDUE	Secretaría de Desarrollo Urbano y Ecología (Mexican Ministry of Urban Development and Ecology)
SEGOB	Secretaría de Gobernación (Mexican Ministry of the Interior)
SEMARNAP	Secretaría del Medio Ambiente, Recursos Naturales y Pesca (Mexican Ministry of the Environment, Natural Resources and Fisheries)

SEMARNAT	Secretaría de Medio Ambiente Recursos Naturales (Mexican Ministry of the Environment and Natural Resources)
SGBUCM	Artefacto de geomática (geomatic tool)
SICLIMA	Sistema de procesamiento de información climática (Query System and Weather Information Processing in Mexico)
SMA	Secretaría del Medio Ambiente (Ministry of Environment in Mexico City)
SMA- GDF	Secretaría del Medio Ambiente del Gobierno del Distrito Federal (Environment Ministry of Mexico City)
SMN	Servicio Meteorológico Nacional (National Weather Service)
SMOC	Sound Management of Chemicals
SNI	Sistema Nacional de Investigadores (National Researchers System)
SPE	solid-phase extraction
Spial	Specificity in alignments; tool for the comparative analysis of two alignments of evolutionarily related sequences that differ in their function
SPOT	Système Probatoire d'Observation de la Terre, later: Satellite Pour l'Observation de la Terre (French satellite system and company)
SRH	Secretaría de Recursos Hidráulicos (Mexican Ministry of Water Resources)
SRTM	Shuttle Radar Topographic Mission
SS	spring–summer
SSEB	Southern States Energy Board
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TBI	Trent Biotic Index
TDEM	Time Domain Electromagnetic Transitory Method
TEMs	transient electromagnetic soundings
THQ	tetrahydroquinone
TIR	thermal infrared
TMCF	tropical montane cloud forest
TPBS	Toxic, Persistent, and Bioaccumulable Substances
TPH	Total Petroleum Hydrocarbons
TPR	space precipitation radar
TPSS	Thin Plate Smoothing Spline
TRIMS	Triple Ring Infiltrometer at Multiple Suction
TRMM	Tropical Rainfall Measurement Mission
TSAVI	Transformed Soil-Adjusted Vegetation Index
TSS	total suspended solids
UAA	Universidad Autónoma de Aguascalientes (Autonomous University of Aguascalientes)
UABC	Universidad Autónoma de Baja California (Autonomous University of Baja California)
UAFB	upflow anaerobic fixed bed
UAM	Universidad Autónoma Metropolitana (Autonomous Metropolitan University)
UANL	Universidad Autónoma de Nuevo León (Autonomous University of Nuevo Leon)
UAS	Universidad Autónoma de Sinaloa (Autonomous University of Sinaloa)
UASB	Upflow Anaerobic Sludge Blanket
UASLP	Universidad Autónoma de San Luis Potosí (Autonomous University of San Luis Potosi)
UAY	Universidad Autónoma de Yucatán (Autonomous University of Yucatan)
UN	United Nations
UNAM	Universidad Nacional Autónoma de México (National Autonomous University of Mexico)
UNCCD	United Nations Convention to Combat Desertification
UNCSD	United Nations Commission on Sustainable Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Education, Science and Cultural Organization
UNFCCC	United Framework Convention on Climate Change
UNISON	Universidad de Sonora (University of Sonora)
UNOSAT	United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme
UN-WWAP	United Nations Water Development Report
USCS	Unified Soil Classification System
USEPA	United States Environment Protection Agency
USGS	United States Geological Survey
UV	ultra violet
VI	vegetation indices
VIRS	visible ultraviolet scanner
VIS	vegetation-impervious surface-soil
VMB	Valley of Mexico Basin
VSS	volatile suspended solids
WEC	World Environmental Centre
WHO	World Health Organization
WQI	water quality index
WRI	World Resources Institute [Washington, D.C.]

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