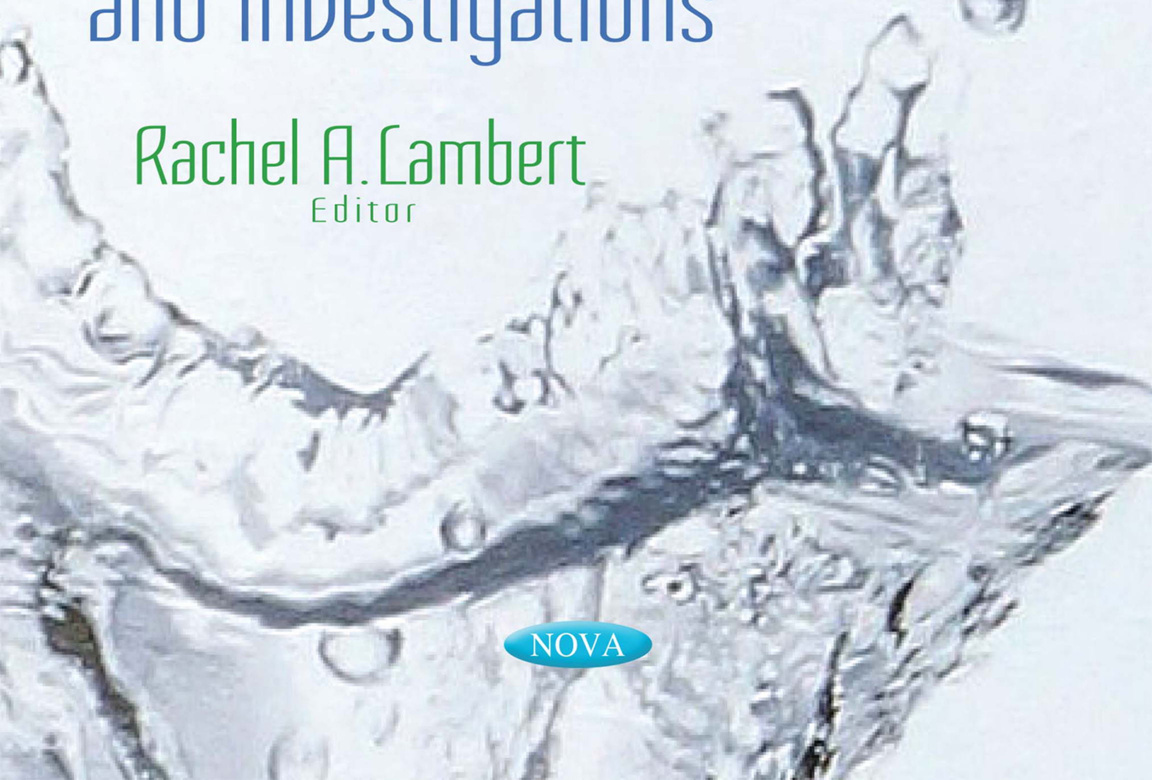
Water Resource Planning, Development and Management

Water Resources

Systems, Management and Investigations

Rachel A. Cambert
Editor



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WATER RESOURCE PLANNING, DEVELOPMENT AND MANAGEMENT

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SYSTEMS, MANAGEMENT AND INVESTIGATIONS

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CONTENTS

PREFACE

This book provides new research on water resources. Chapter One discusses water resource management and intelligent monitoring systems for reservoirs. Chapter Two describes actions applied to the management of water resources in the region of La Plata in Argentina. Chapter Three analyzes the physico-chemical characteristics of natural waters in a drainage system of northern Xinjiang (Central Asia) to provide additional information to the readers on the chemical evolution and recharge mechanism of natural waters in an arid environment. Chapter Four reviews flow alterations and then employs a modeling system and databases for the river systems of Texas to investigate characteristics of river flows and long-term impacts thereto resulting from development and other causative factors.

Chapter 1 – Due to the severe shortage of water resources in mainland China, dire consequences may be expected if rational and comprehensive water resources management systems are not developed and put into application. Poor management of water resources of decades long has led to a series of problems like water pollution, floods in cities, uncertain drinking water quality in rural areas and so on. The contents in this chapter mainly cover four systems developed for water resources management and they are the water release system (WRS) for reservoir, water resources facility management system (WRFS), water safety management system for rural areas, and inspection system for hydraulic engineering. The system architecture and the analysis and development methodologies for each system are also introduced here. Computer languages or framework like SQL Server, Microsoft Access, .Net, Visual Studio and C# are chosen to develop these systems.

Chapter 2 – The paper describes actions applied to the management of water resources in the region of La Plata (Buenos Aires Province, Argentina). The overexploitation of groundwater has modified the hydraulic conditions and, at the same time, has affected the hydrochemical characteristics by favoring contamination from human wastes. At present, the average exploited groundwater volume for human consumption is 73 hm^3/y and since a substantial increase of demand for water is predicted in future years, sustainable groundwater exploitation becomes essential. Rational management is necessary to reach a balance between water demands and groundwater conservation to avoid the extreme deterioration of water quality.

Chapter 3 – This paper analyzed the physico-chemical characteristics of natural waters in a drainage system of northern Xinjiang (Central Asia) for an identification of the geological evolution and recharge mechanism of natural waters in an arid environment. The studied waters are different in mineralization but are typically carbonate rivers and alkaline in nature. No Cl-dominated water type occurs, indicating an early stage of water evolution. Regolith and geomorphological parameters controlling ground-surface temperature may play a large role in the water geological evolution. Three main morphological and hydrological units are reflected in water physico-chemistry. Climate influences the salinization of natural waters substantially. Direct recharge from seasonal snow and ice-melt water and infiltration of rain into the ground are significant recharge processes for natural waters, but recharge from potential deep groundwater may be less important. The enrichment of ions in lakes has been mainly caused by evaporation rather than through the quality of the recharged water.

Chapter 4 – Flows of rivers throughout the world have been altered by population and economic growth and accompanying water resources development. River flow characteristics are changed by construction of dams and other facilities to control floods, generate hydroelectric energy, and provide reliable water supplies, diversions for agricultural, municipal, and industrial needs, and return flows from surface and groundwater supplies. Impacts on hydrology and water availability associated with climate change due to global warming are also of major concern in hydrologic science and water management. Alterations in flow characteristics differ greatly across the spectrum from low flows to median flows to infrequent extreme flood flows. Gradual permanent increases or decreases in stream flow may be difficult to detect due to the great continuous natural variability that hides long-term trends. This chapter reviews studies of flow alterations found in the literature and then employs a modeling system and databases for the river systems of

Texas to investigate characteristics of river flows and long-term impacts thereto resulting from development and other causative factors. Researchers have applied statistical trend analysis methods, watershed precipitation-runoff models, and river-reservoir system management models to quantify flow alterations for river systems throughout the world. Flow alterations in Texas are illustrative of river systems in many other regions of the world. A water availability modeling system developed to manage water resources in Texas provides a unique opportunity to explore alterations to river flows for a broad diverse range of climate and hydrologic conditions, population and economic growth, and water resources development and management practices. Trends of long-term changes in precipitation during 1940-2015 are not evident in Texas. Flows for reaches of major rivers have been impacted significantly, in some cases dramatically, by water development. The flow increases and decreases vary greatly with location.

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Chapter 1

WATER RESOURCE MANAGEMENT AND INTELLIGENT MONITORING SYSTEM FOR RESERVOIR

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ABSTRACT

Due to the severe shortage of water resources in mainland China, dire consequences may be expected if rational and comprehensive water resources management systems are not developed and put into application. Poor management of water resources of decades long has led to a series of problems like water pollution, floods in cities, uncertain drinking water quality in rural areas and so on. The contents in this chapter mainly cover four systems developed for water resources management and they are the water release system (WRS) for reservoir, water resources facility management system (WRFS), water safety management system for rural areas, and inspection system for hydraulic engineering. The system architecture and the analysis and development methodologies for each system are also introduced here. Computer languages or framework like SQL Server, Microsoft Access, .Net, Visual Studio and C# are chosen to develop these systems.

Keywords: water resources, facility management, monitoring system, modelling

1. INTRODUCTION

Freshwater resources, which are the most useful water resources for human in terms of convenience, are mainly found in rivers, streams and lakes. Generally, water resources are mainly used for water supply for human and livestock, industrial use, irrigation, navigation, power generation, fish farming, environmental conservation and so on. Unfortunately, an ever growing global population means an ever growing fresh water demand in most areas, particularly in the areas of industry use, irrigation for agriculture, and the water supply for human and livestock. And increased water demand may lead to the drilling of deeper wells, therefore may impair ground water quality by increasing dissolved mineral concentrations and inducing saline or polluted surface water from other aquifer into the freshwater aquifer. Industry use may also cause the surface and subsurface water pollution.

The rapid social and economic development in mainland China is putting the river basins in North China under even more pressure [1]. Agricultural and industrial use of fresh water and the population growth will further increase the demand for water. In addition, the ongoing urbanization process in mainland China is expected to last for at least one or two decades long.

Without strategic planning, this process generally increases the water runoff, causing storm water flooding and water source pollution problems. As cities grow larger and water demand increases, people and businesses are forced to look further to meet their projected water needs and to increase the use of rainfall. This may influence and change the water flow pattern of a region and the consequential impact on the environment could be very serious because the accurate prediction on floods or droughts caused by rapid urbanization become even more difficult. In recent years, flooding in many Chinese cities including the cities in North China has become the ordinary scenarios in the summer time and the social-economy losses have been huge [2]. Current situation urges the implementation of the comprehensive water s management.

To utilize fresh water resource in a comprehensive manner means we need to have a better understanding of the relationships among subsurface water, surface water, precipitation (rainfall), water conservation, and of the key factors that influence the water flow among rivers, lakes and streams. The realization of such a better understanding requires detailed information on all kinds of water resources and that is why some interests are focused on the monitoring system for water resources. In addition, since the water quality varies greatly in the vast rural areas in mainland China due to water pollution and overuse of the subsurface water [1], the water safety management system that specifically aims at monitoring the drinking water safety in rural areas is also introduced. Besides the shortage of water resources, geologically, the water resource distribution is hugely uneven and the crops in North China generally grow in the arid condition. The facts of China's huge population and its relatively scarce water resources determine that water resource facilities play very important role in the economy of China. Therefore, the inspection of hydraulic engineering and the monitoring of water resource facility, which are fundamental for the water resources management, are also elaborated in the chapter. Water resources management involves many aspects such as: 1) monitoring the amount, the quality, the temperature, and the potential hydropower production of water resources; 2) the channelization of the water flow, the fresh water allocation, the water conservation, the protection of watershed, the flood/drought management and the early warning or alarming; 3) the entire life management of water resource facilities; 4) the wastewater collection, purification and its re-use; 5) the morphological or profile changes of water channels; 5) the precipitation (rainfall) and the water solubility of affected zones or regions.

The current situation urges the intelligent systems for the effective and efficient utilization of water resources. Modern technologies like the information technology (IT), geologic information system (GIS), global positioning system (GPS), remote sensing (RS) technology, information communication technology (ICT), and internet of things (IoT) technology, have the ability to generate huge volume of raw data and information useful for the study of the change and evolution of water resources in a specific area or region [3-6, 10]. The accurate and real time information on water resources can also be used to allocate fresh water rationally to meet the water demands for irrigation, navigation and industry use, and to provide sound guidance for power generation and water conservation. Furthermore, reliable prediction can also be made on the natural disasters like flood, drought, landslide and the areas that could be seriously affected. Therefore, early warning can be issued to avoid or mitigate the potential damage to human and property. In this chapter, based on these modern technologies, four systems related to water resources management are introduced. And they focus on the management of reservoir, the mechanical structure safety evaluation of hydraulic engineering, the drinking water quality monitoring in rural areas, and the inspection of hydraulic engineering, respectively.

2. Water Release System (WRS) of the Reservoir

2.1. System Functions

More crop plantation and less flooding zones determine that more floods are likely to occur in mainland China if no appropriate measures are put in place. The hazards of flood include the erosion of the soil, damage to infrastructure, transportation disruption, crop loss, water contamination, human and property loss and so on. Flood can also change the river channel or river bed profile. In short, floods can be such devastating disasters that we all can be affected to some degree. Reservoirs, which act as the manmade lakes in some way, are more flexible in the redistribution/allocation of water resources. As more natural lakes vanish due to either the reclamation or the change of subsurface water flow, the role of reservoirs in mitigating floods and serving irrigation and/or navigation tends to be more significant. As for the role in the mitigation of flooding hazards, the key lies in quick and reliable prediction of surface and subsurface water flow in certain area with the consideration of geological situations and the precipitation (rainfall).

Until recent years, for the vast majority of reservoirs in mainland China there has been no reliable method and mechanism to timely adjust the volume of the water storage of reservoir in real time feature by taking into the consideration of the situations of precipitation like the rainfall amount, its distribution and the factors influencing the water flow like the geographic/ geological conditions of river basins. Accordingly, the plan for the timing and the amount of water admitting or releasing has generally been based on experiences and considerably less reliable. Obviously, the optimized plan has been simply unavailable owing to the lack of fundamental data for meaningful analyses and modelling.

As mentioned previously, various modern technologies like the GIS, GPS, IT, ICT and IoT technologies provide very solid bases for water release system (WRS) development because most information and data related to water resources become available and accessible. For example, the application of IoT technologies in the gauging stations, the weather monitoring stations and the reservoir monitoring sites has strengthened the capability of collecting the information on the hydrological parameters like the speed, the volume/amount, the viscosity of water flow, velocity gradient, and even the river bed profiles. The analysis and prediction by WRS system involves specific algorithms and fundamental data collection. Through simulation WRS system provides with a series of services: 1) providing the plans for the daily management of the reservoir and quick response at the time of emergency; 2) warning for floods in possibly affected areas; 3) online information inquiry for residents; 4) refinement of simulation model for better prediction on flood and drought; 5) uploading and sharing core data among the government agencies; 6) monitoring the water quality to ensure the safety of human and live-stocks; 7) monitoring the safety of water resource facilities.

Obviously, a meaningful water management system development needs not only good understanding and study of water resource systems, possession of the requisite mathematical tools and the systemic methodology skills, but also good understanding of the environmental engineering, the economic and social aspects of water resources management. The ultimate goal is to provide the planners or the decision makers with the understandable, useful, accurate and timely information.

2.2. WRS System Architecture

As illustrated in Figure 1, the architecture of WRS system has three layers, i.e., the user layer, the application layer and the basic information (data) layer. All the computation and data manipulation are based on the data and information in the databases for the historic records or documents, the weather forecast, the real time precipitation (rainfall), the real time situation of rivers/streams, and the real time state or situation of reservoirs. Operations like the data input, information extraction, prediction, water discharge, database management, and the system maintenance can be fulfilled *via* the user interfaces.

Different authorities are defined for different users – ordinary users can only use basic functions of the system while the administrators have the top authority and can do operations like editing the data from GIS system. The user interface layer is used to display various interfaces for users. User can input and inquiry information *via* the user interfaces.

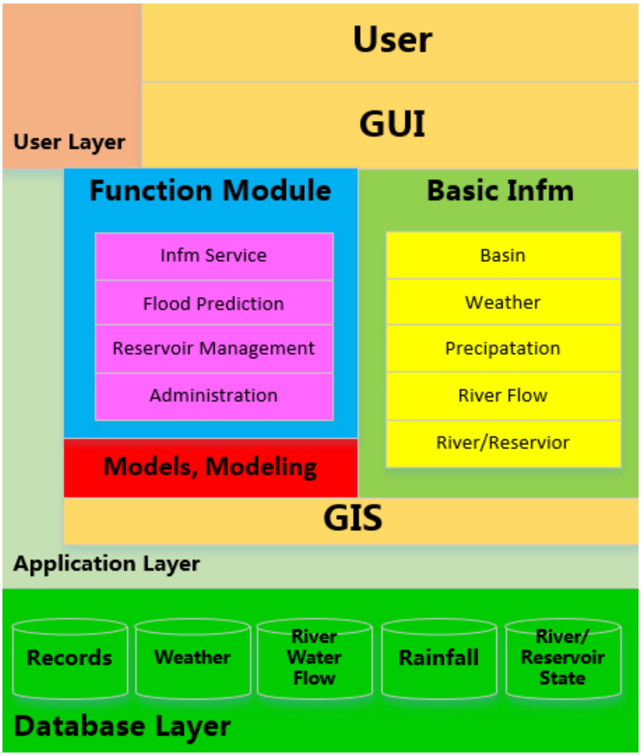


Figure 1. Architecture for WRS system.

The application layer mainly consists of two parts: the GIS module and the function modules. The application layer serves the purposes and functions of WRS system, for example, the functions for the visualization of the GIS data and the display of relevant information inquired by users. Computing and modeling modules usually run operations on servers or the cloud platform and cannot be accessed or interfered by ordinary users. The data in databases like the one for GIS information are largely static while the data for the water flow and precipitation are characteristically dynamic. Some data need to be acquired or extracted from other databases if real time information is needed for computation or simulation.

2.3. Methodology for WRS System Development

This WRS system is applied for the reservoirs in the Dongjiang River Basin for the flood prediction, the water release plan formation, and the daily reservoir management as well. The methodology for the development of the WRS system is as:

a) All useful data and information are categorized and collected in different databases. They include the information on the Dongjiang River Basin and the reservoirs in the region, the records and documents for the previous rainfalls and floods, the model parameters for water release and/or admittance and so on. All the simulation and analysis results generated by computation are also collected and stored in one database.
b) The information and data for the forecasted precipitations (rainfall) are input and used to make flood prediction and to provide plans for reservoir water release. The prediction and plan can be modified as the updated information and data are factored in the computation or simulation. The updated information and data are collected by the gauging stations in the Dongjiang River Basin.
c) It should be emphasized here that the final decision on the reservoir water release plan is made by the government agencies in mainland China according to the rules and laws.

2.4. Functions of WRS System

The main functions of the WRS system are:

a) Data and information input, editing, display, comprehension, and inquiry of the information on the precipitation (rainfall) and the real time situation of rivers/streams and reservoirs;
b) Determination and modification of values of model parameters for predication and simulation. For example, the change of parameters leads to different precipitation distribution models;
c) Flood stage estimation, upstream or downstream flood prediction, plan formation for reservoir water release;
d) Numerical simulation and refinement of expert systems of WRS system;
e) Management of the operation activities, mainly the operation of the water gate system;
f) System management which includes the management of the databases and system maintenance;
g) Database management including data dictionary design and table structure design, data inquiry and extraction, database maintenance and so on;
h) Sharing the data and information with analysts, operators, experts and decision makers *via* the electronic mail, the instant message and the internet.

2.5 Applications of WRS System

2.5.1. Inquiry of the Real Time Information and the Data in the Dongjiang River Basin

Geographic information systems (GIS) have the capability to provide with the improved spatial analysis and information display. Using GIS technology, the hydrological data and their representation on the digital map of the Dongjiang River Basin can be displayed graphically and visually, as shown in Figure 2. This graphic user interface (GUI) can present the information on the precipitation (rainfall) distribution, the geographic center of the storm rain, the motion of the clouds, and the geological features in an interactive fashion. Isohyetal map, which is used to show the rainfall distribution by depicting the curves of equal rainfall, is also available in this system and an example is given in Figure 3.

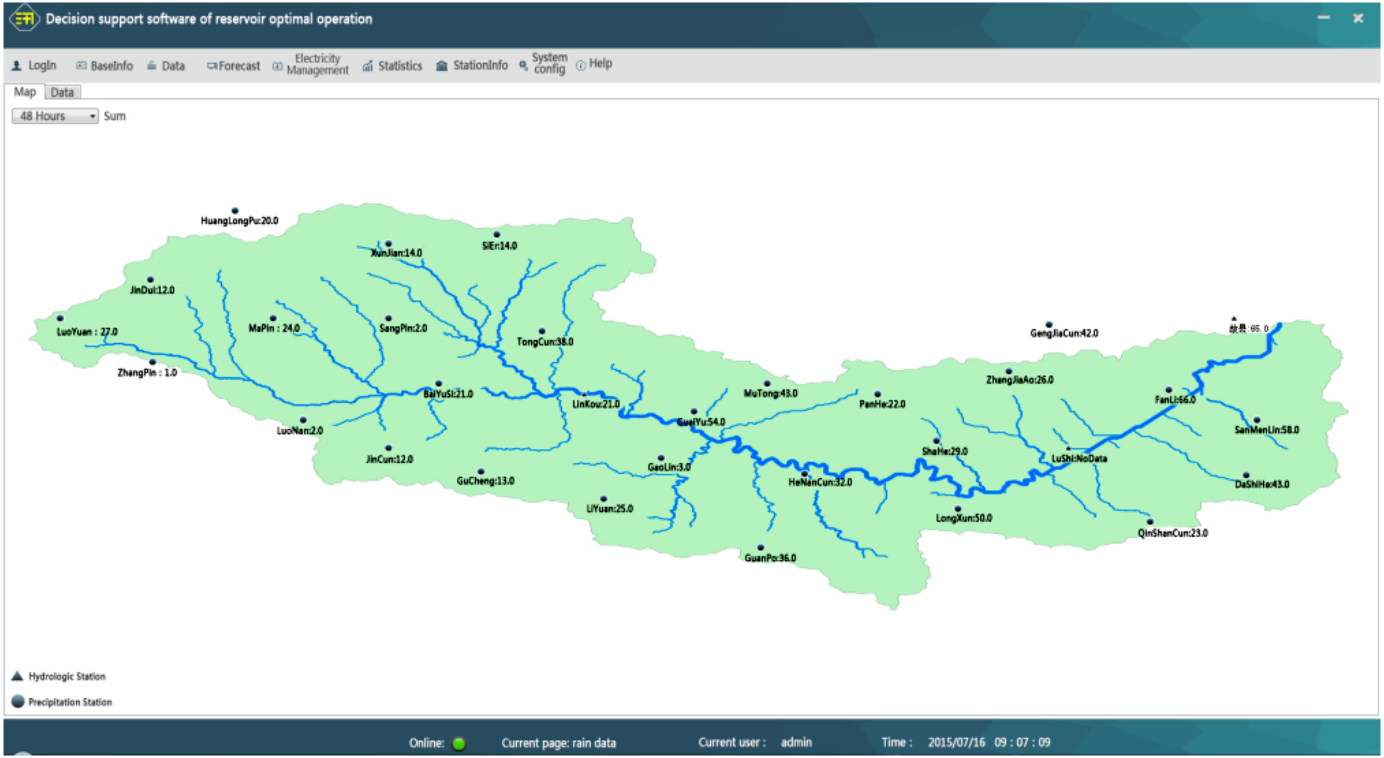


Figure 2. GIS information display.

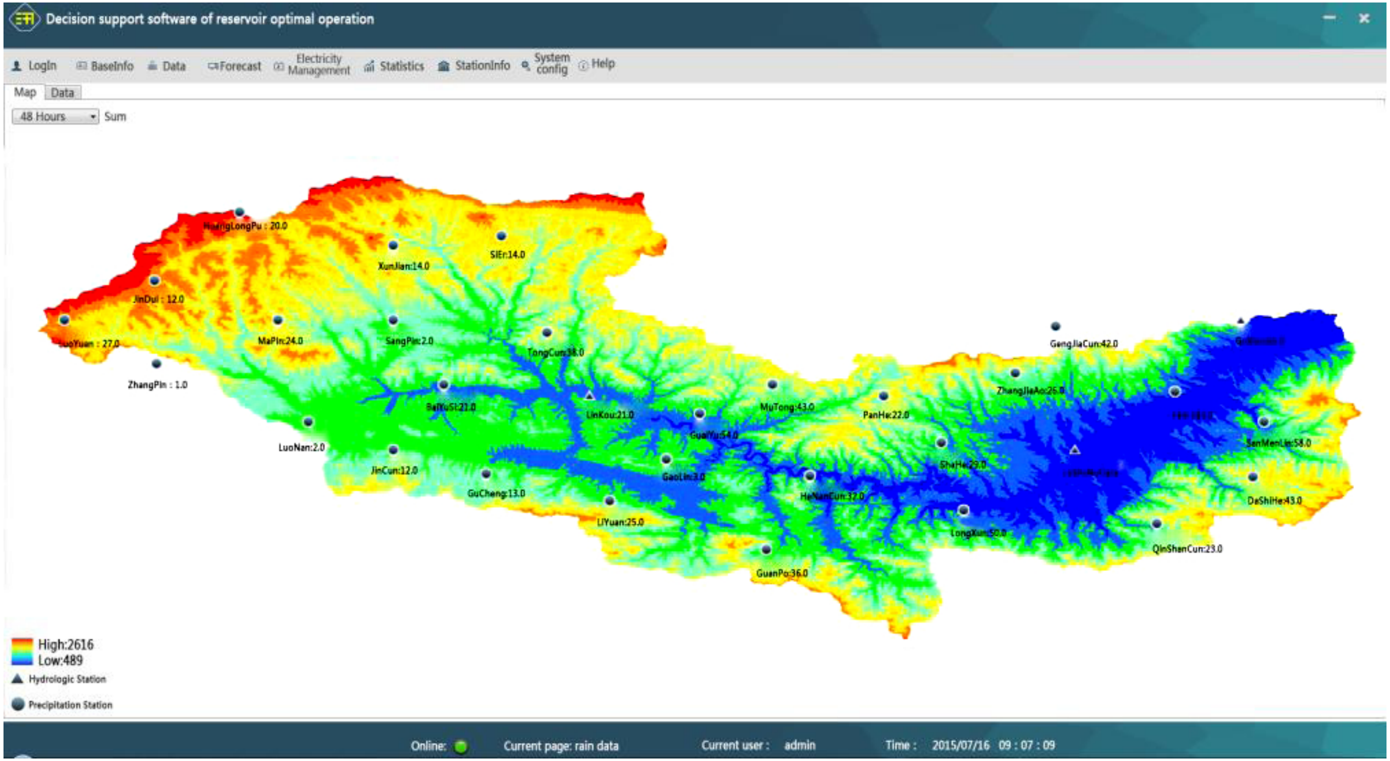


Figure 3. Real time rainfall distribution.

2.5.2. Flood Prediction

Flood is the major concerns for most of us and that is why its prediction has been attracting great interests and attention. There exist various prediction models now. Some are traditional ones which mainly rely on experiences while some models rely much more on real time data and information to facilitate prediction. Generally speaking, modelling is a process aiming at clearer thinking and more informed decision-making. The approach involves problem recognition, system definition, identification of goals or objectives, evaluation of various alternatives, and the effective communication of the information to deciders and operators. Widely accepted models for water flow simulation and related researches [13, 15-19] are described as below:

2.5.2.1. Probability Analysis

Flood probability/frequencies can be determined if data is available for the discharge of the river over an extended period of time [18-19]. Using these data, the statistical analysis can be applied to determine the frequency or probability of a given discharge of a river [20-24]. The data for the discharge are traditionally provided by gaging stations along the river. And Weibull distribution is often adopted to statistically describe or estimate the recurrence interval [41-42]. A simple approach is plotting the number of years of record, and the rank for each peak discharge in so called Weibull probability plotting paper. An example is given in Figure 4.

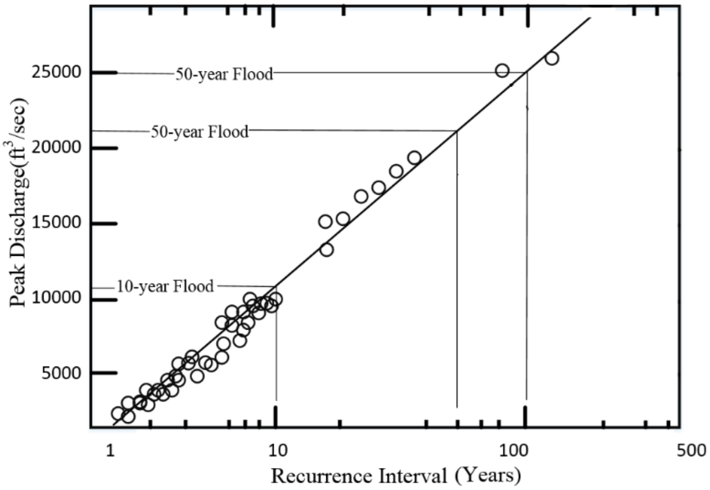


Figure 4. Flood prediction based on historical records.

Usually the recurrence interval is plotted on a logarithmic scale. A best-fit line is then plotted through the data points. From the best-fit line, the peak discharge associated with a flood with a recurrence interval of a certain time period can be determined or estimated. Many commercial codes are also available now to make the Weibull distribution analysis.

2.5.2.2. Simulation Models

2.5.2.2.1. Modeling Approaches

The rapid developments in computer technology – from PCs and servers to today's cloud platform– have improved the computation capacity and capability greatly [10]. These developments constitute the bases for the sophisticated analyses and simulation. And modeling for a complicated system like water resources management system becomes feasible now. Great development and application of IT technology in the water resources management means big data concerning more parameters are available. And those data not only contain information, but also can be used to find relationships among those parameters. Thus, modeling can be carried out and further simulation can be further made for analyses or prediction. Models based on data range from the commonly used regression models to models based on, for example, the evolutionary or biological processes. They are among a wide range of data mining tools designed to identify and abstract information and/or relationships from large sets of data.

There are a group of probabilistic approaches known as evolutionary algorithms (EAs). Such algorithms include genetic algorithms (GAs), genetic or evolutionary programming (GP or EP) and evolutionary strategy (ES) [9]. Each of these methods has many varieties and all use computational methods based on natural evolutionary processes and machine learning. Artificial neural networks (ANN) approach [7-8, 11-13] is also a popular method to emulate larger, deterministic, process-oriented models.

The basic structure of an ANN is shown in Figure 5. The input layer consists of nodes that receive an input. The hidden layer(s) typically receive the transferred weighted inputs from the input layer or previous hidden layer, perform the transformations, and pass the output to the next adjacent layer, which can be another hidden layer or the output layer. The nodes of the output layer receive the hidden layer output and send it to the user. For example, the inputs to simulation models can include a much longer time series of hydrological, economic and environmental data for the precipitation (rainfall), river/stream water flows, water supply demands, pollutant loadings and so on.

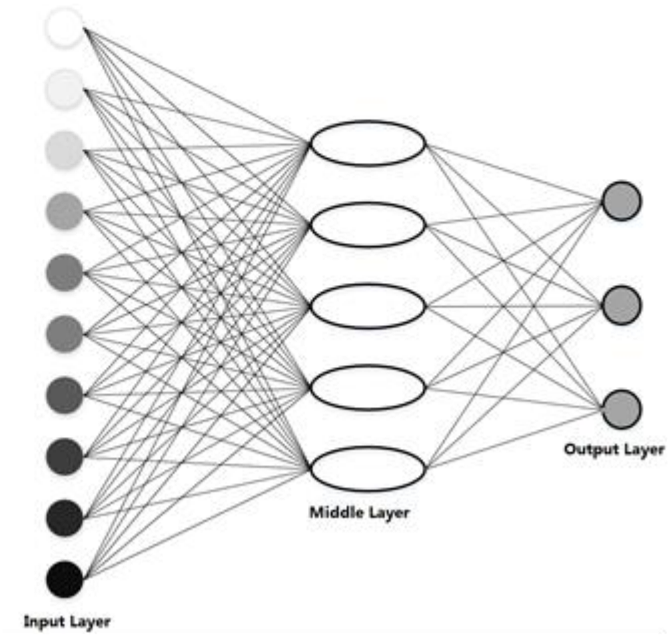


Figure 5. Schematic ANN architecture and components.

2.5.2.2.2. Parameters of Interests for Prediction Simulation

The hydrological parameters of the water flow and the profiles of the river bed are necessary for the calculation of the water discharge in a river/stream. Assuming the water flow is laminar type with a constant speed of water flow, the discharge can be easily estimated by multiplying the cross sectional area with the speed of water flow, which may be written as Eq.1.

$$V_d = V\ A \qquad (1)$$

where V_d is the value of discharge and V and A are the water flow speed and the cross sectional area, respectively. Emphasis should be made here that the profiles of the river bed is generally irregular (as schematically shown in Figure 6) and numerical integration approach can be used to calculate the cross sectional area for different state of water flow.

Obviously, the discharge capacity of a river/stream is closely related to the profiles of the river bed and is not linearly proportional to the depth of the river flow (see Figure 6). In reality, there exists velocity gradient and the velocity distribution is related to the meandering characteristics of a river/stream (as shown in Figure 7).

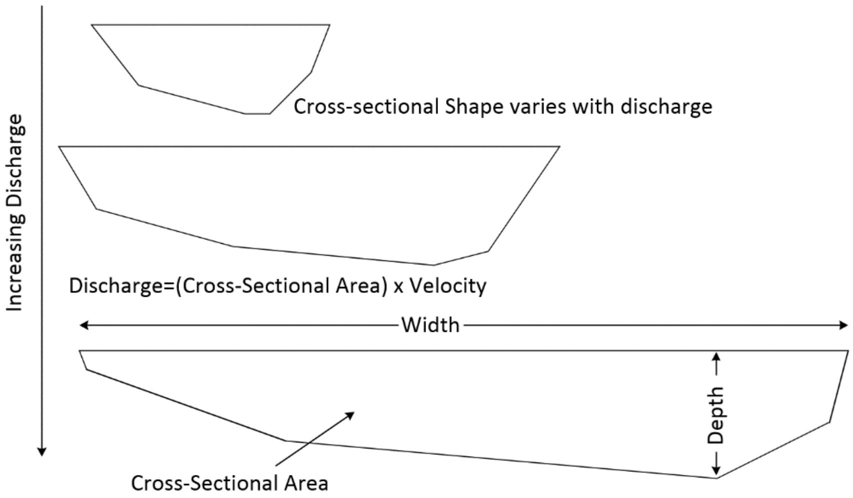


Figure 6. Relationship between river bed profile and discharge.

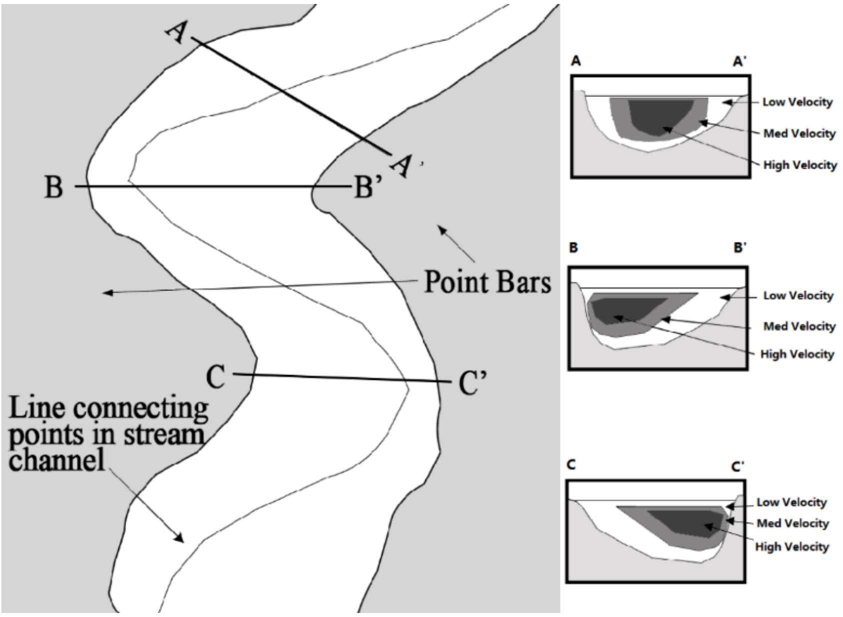


Figure 7. Water flow velocity in a river.

2.5.3. Precipitation and Environmental Parameters

The rainfall water may be evaporated and returns to the atmosphere, infiltrate the soil and become part of the groundwater system, or be intercepted by vegetation/crops. The rest eventually flows into rivers/streams and is defined as runoff. In general, we have the runoff amount as:

$$V_r = V_p - V_f - V_t - V_e \tag{2}$$

where V_r, V_p, V_f, V_t and V_e denote the amount of the runoff, and the water amounts for the precipitation (rainfall), the infiltration, the interception, and the evaporation, respectively. Many hydrological and environmental factors determine the amount of runoff towards rivers/streams by influencing the behaviors of infiltration, interception and evaporation.

Evaporation tends to be the least of these quantities, particularly over short periods of time, and thus precipitation, infiltration, and interception are the most important variables that determine the runoff and eventual water discharge into rivers/streams. The soil type and the degree of saturation also have direct influence in the infiltration while the interception is related to the vegetation and its components. With the data and information from sources like the weather forecast, the gauging stations along rivers/streams, and the regional observatories, modeling can be done using the approaches previously mentioned. For example, if the geographical rainfall distribution in a particular area is clear and the infiltration, interception, and evaporation models are available, then the state of water flow in rivers/streams can be simulated and the possibility of flooding, the possible weak locations, and the lag time can be predicted. Lag time is defined to be the time difference between when heavy precipitation occurs and when peak discharge occurs in the rivers/streams. Its estimation contributes a lot to early warning for the public and reservoir water release planning.

Several models and approaches can be used to predict the river/stream runoff amount based on the weather forecast, real time data collected by gauging stations, the historic records or documents, and the mathematical algorithms for computation or simulation. An example for the case of excessive infiltration is given in Figure 8.

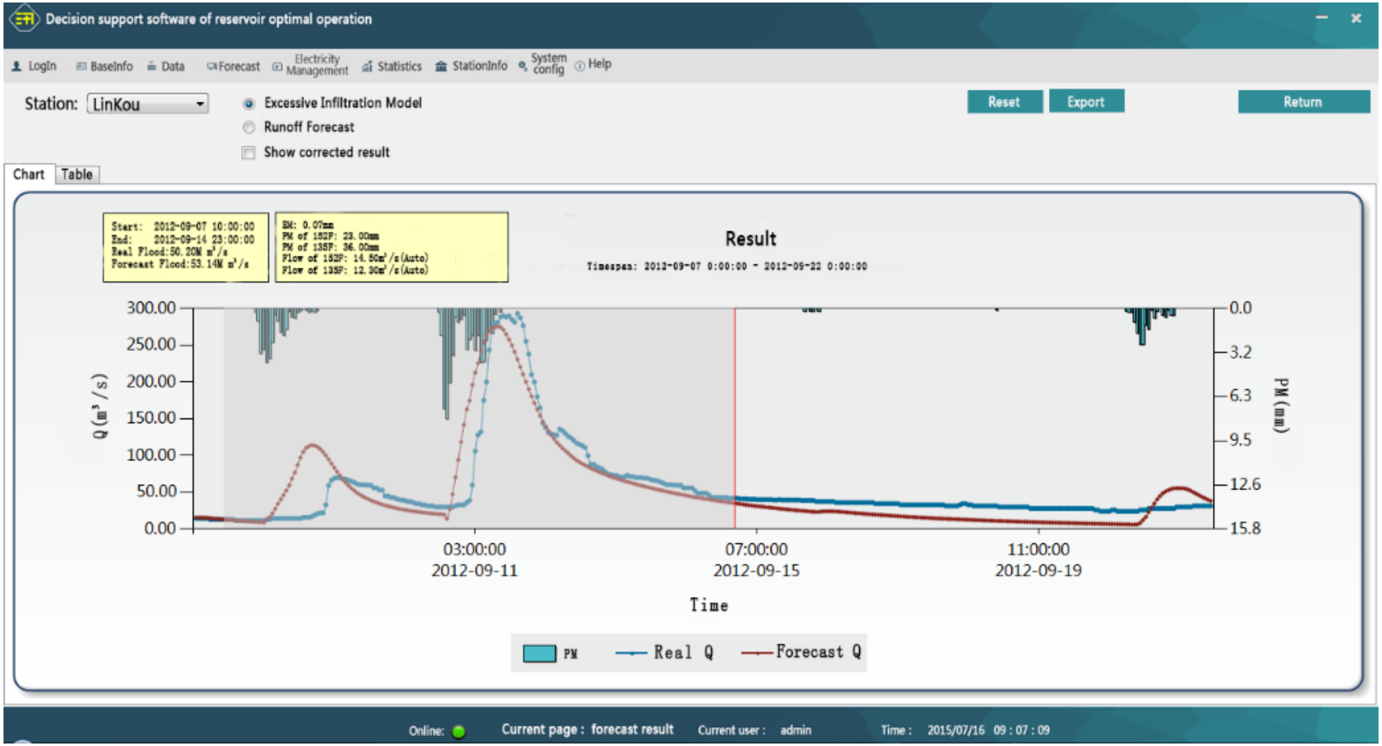


Figure 8. Flood prediction for the state of excessive infiltration.

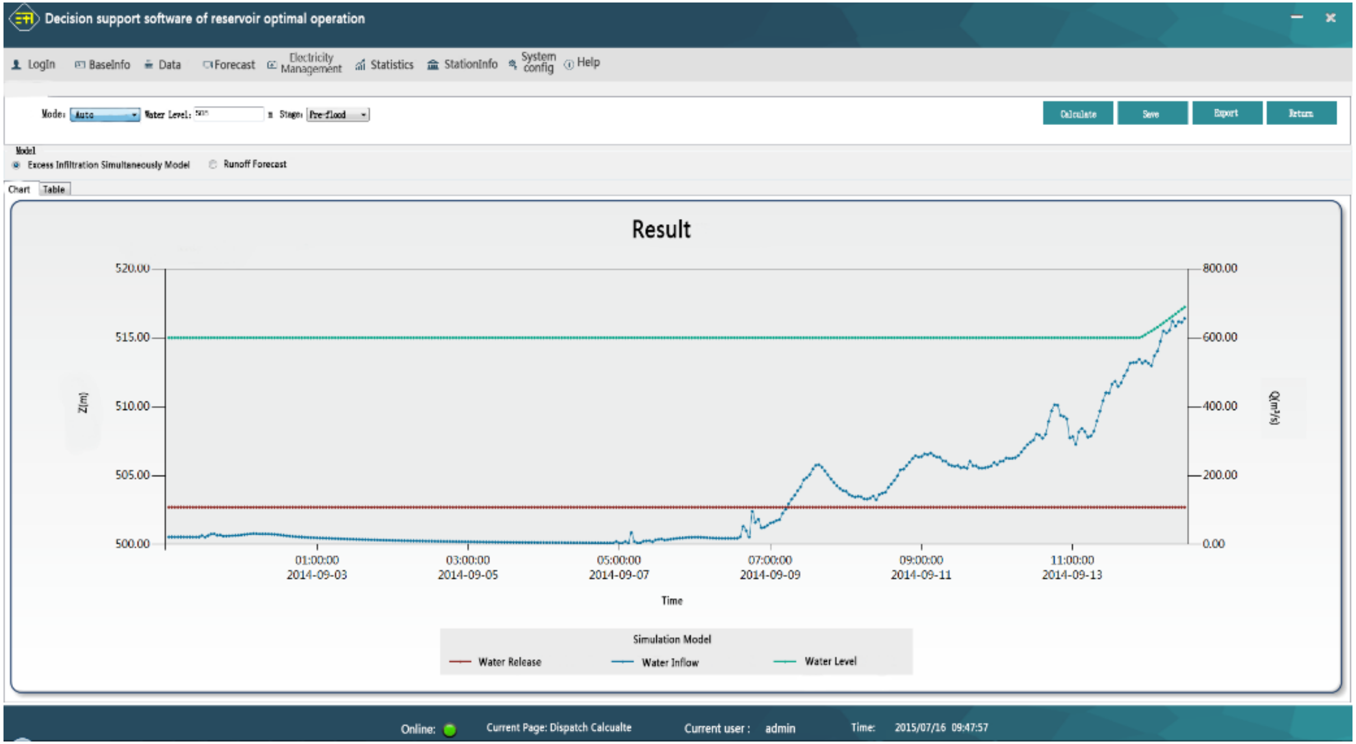
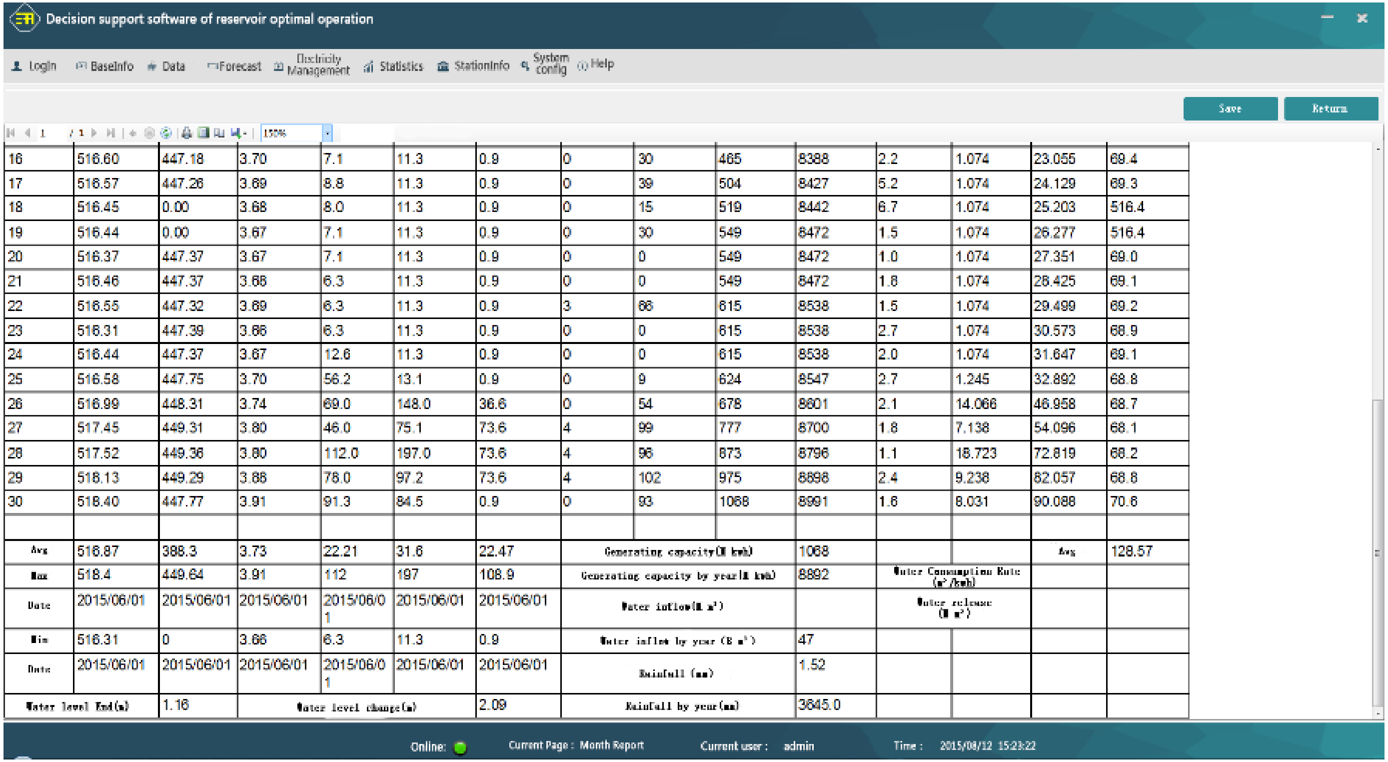


Figure 9. Simulation for reservoir release plan.



16	516.60	447.18	3.70	7.1	11.3	0.9	0	30	465	8388	2.2	1.074	23.055	69.4
17	516.57	447.28	3.69	8.8	11.3	0.9	0	39	504	8427	5.2	1.074	24.129	69.3
18	516.45	0.00	3.68	8.0	11.3	0.9	0	15	519	8442	6.7	1.074	25.203	516.4
19	516.44	0.00	3.67	7.1	11.3	0.9	0	30	549	8472	1.5	1.074	26.277	516.4
20	516.37	447.37	3.67	7.1	11.3	0.9	0	0	549	8472	1.0	1.074	27.351	69.0
21	516.46	447.37	3.68	6.3	11.3	0.9	0	0	549	8472	1.8	1.074	28.425	69.1
22	516.55	447.32	3.69	6.3	11.3	0.9	3	66	615	8538	1.5	1.074	29.499	69.2
23	516.31	447.39	3.66	6.3	11.3	0.9	0	0	615	8538	2.7	1.074	30.573	68.9
24	516.44	447.37	3.67	12.6	11.3	0.9	0	0	615	8538	2.0	1.074	31.647	69.1
25	516.58	447.75	3.70	56.2	13.1	0.9	0	9	624	8547	2.7	1.245	32.892	68.8
26	516.99	448.31	3.74	69.0	148.0	36.6	0	54	678	8601	2.1	14.066	46.958	68.7
27	517.45	449.31	3.80	46.0	75.1	73.6	4	99	777	8700	1.8	7.138	54.096	68.1
28	517.52	449.36	3.80	112.0	197.0	73.6	4	96	873	8796	1.1	18.723	72.819	68.2
29	518.13	449.29	3.86	76.0	97.2	73.6	4	102	975	8898	2.4	9.238	82.057	68.8
30	518.40	447.77	3.91	91.3	84.5	0.9	0	93	1068	8991	1.6	8.031	90.088	70.6
Avg	516.87	388.3	3.73	22.21	31.6	22.47	Generating capacity(M kwh)			1068			Avg	128.57
Max	518.4	449.64	3.91	112	197	108.9	Generating capacity by year(M kwh)			8892	Water Consumption Rate (m³/kwh)			
Date	2015/06/01	2015/06/01	2015/06/01	2015/06/01	2015/06/01	2015/06/01	Water inflow(M m³)				Water release (M m³)			
Min	516.31	0	3.66	6.3	11.3	0.9	Water inflow by year (B m³)			47				
Date	2015/06/01	2015/06/01	2015/06/01	2015/06/01	2015/06/01	2015/06/01	Rainfall (mm)			1.52				
Water level End(m)		1.16	Water level change(m)			2.09	Rainfall by year(mm)			3645.0				

Figure 10. Reservoir daily information management.

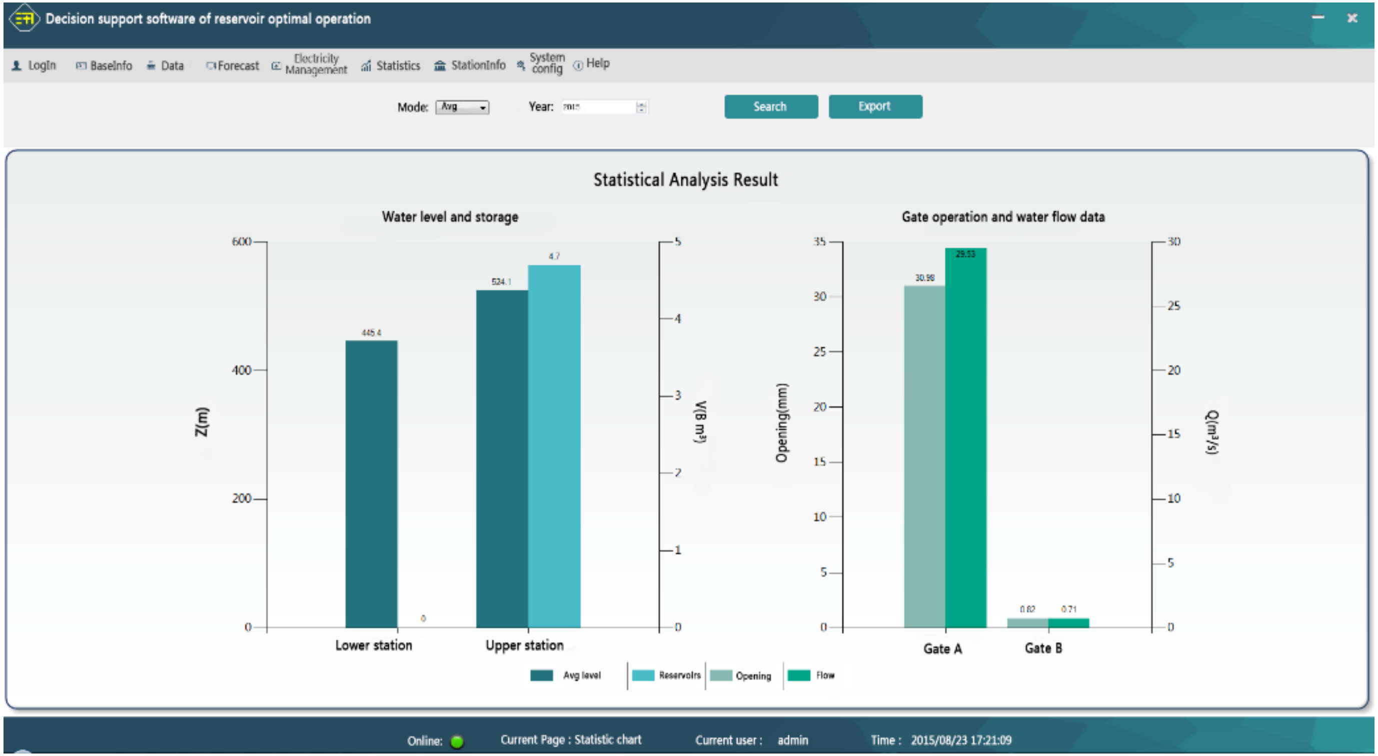


Figure 11. Statistical analyses for the state and operation of reservoir.

2.6. Reservoir Water Release Plan

A lot of factors are taken into account to form the final decision on the water release plan. In mainland China, the plan formulated by WRS system is considered as an important factor while the collective decision by a group of experts in hydraulic, hydro-geologic, hydrological, ecologic and environmental engineering fields also contributes to the final water release plan. In any circumstances, the volume of water stored in a reservoir cannot exceed the reservoir’s storage capacity.

Since the storage volume and the reservoir capacity over the time period of raining in a river basin area may be unknown, a proper water release plan can only be finalized through a series of simulations on the evolution of the real time storage volume of a reservoir and the water flow of the upstream of a river, and the inflow into the reservoir when different key parameters like the timing, the time period, and the rainfall amount are input and considered. An example is given in Figure 9.

2.7. Daily Reservoir Management

The records for the daily operation and maintenance can be analyzed and the documentation concerning the daily management can be automatically carried out. Obviously, documents for the information on the tools, the consumptive materials, the facilities, and for the situation of the reservoirs, can help with lean reservoir maintenance and good monitoring. Examples are shown in Figures 10 and 11.

3. Water Resource Facility Safety Management System (WRFS)

3.1. Background

Water gates are used for water release and adjustment of water storage and reservoir capacity. Historically, serious consequences have been caused by the faults or failures of the mechanical structures of water gate system. The failure of proper opening and closing of water gates led to disasters in Russia and Spain and huge human losses and economy damage had been made [38]. In mainland China, the unexpected deformation or the destruction of the metallic mechanical structures of the water gate system also led to serious consequences in Qinghai Province [38]. For the case that the mechanical structures of big size are involved, the safety and reliability is very important for the efficient management of the reservoir and the power generation, too. Ironically, the importance of this subject has not raised much attention in mainland China for long time and little work has been done until recent years.

A lot of factors have influence in the safe operation of the water gate system. Typical factors include structural stability, reliability of structures and hydrological parameters of water flow. In short, all the factors that may induce the stress, the deformation or introduce erosion into the mechanical structures of water gate system shall affect the operations of the system.

Traditionally, regular observations on the metallic structures of water gate system are often made by naked eyes. And the real time monitoring of the water gate system essentially does not exist. Due to the lack of the real time data for the stresses, the deformations, the opening and closing forces and the hydrological parameters of water flow, the reliability evaluation and maintenance prediction cannot be carried out and the safety of the reservoir cannot be secured. Obviously, such a bottleneck also hinders the realization of intelligent WRS system.

3.2. Functions of WRFS System

3.2.1. Prediction and Warning Functions

The mechanical structures for the opening and closing of water gate have a long service life. As mentioned above, their reliability has direct impact on the power generation and the comprehensive utilization of water resources. WRFS system has several subsystems to fulfill various functions. The methodology to realize the prediction and warning functions of WRFS system may be described as: 1) database development for mechanical properties and stress/strain distribution; 2) numerical analyses and simulation; 3) development for the expert systems; 4) information collection and analyses for the actual situations; 5) display of the analysis results.

Numerical simulation based on the finite element methods (FEM) is widely used for the computation of the stresses and strains, and the determination of the critical positions in the mechanical structures. Fracture mechanics is used to evaluate the structural safety when surface or subsurface flaws have been detected and measured.

The elastic constants of the annealed metallic materials are isotropic. However, cold-worked metallic beams with various cross section shapes are widely used in engineering structures and the mechanical properties of those beams are usually transversely isotropic. For the structures made of the engineering materials with different mechanical behaviors, the governing equations used for numerical simulations are different, too.

3.2.2. Overall Numerical Simulation

For isotropic materials and one dimensional case, the stress *vs* strain relationship in the range of elastic deformation may be described by the Hooke's Law [33] as given by Eq. 3.

$$\sigma = E\,\varepsilon \tag{3}$$

$$E = 2G(1+\nu),\;\; G = E/(2(1+\nu)),\;\; \nu = E/(2G) - 1 \tag{4}$$

where E is the elastic modulus, i.e., the Young's modulus; σ, ε and ν denote the normal stress , the normal strain and the Poisson's ratio, respectively; G is the shear modulus; The constants of E, ν and G are not independent and their relationships can be found in Eq. 4.

For general cases, i.e., three dimensional (3D) cases, the governing equations can be described in the matrix forms as shown in Eq. 5.

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{bmatrix} = \begin{bmatrix} \hat{E}(1-\nu) & \hat{E}\nu & \hat{E}\nu & 0 & 0 & 0 \\ \hat{E}\nu & \hat{E}(1-\nu) & \hat{E}\nu & 0 & 0 & 0 \\ \hat{E}\nu & \hat{E}\nu & \hat{E}(1-\nu) & 0 & 0 & 0 \\ 0 & 0 & 0 & G & 0 & 0 \\ 0 & 0 & 0 & 0 & G & 0 \\ 0 & 0 & 0 & 0 & 0 & G \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{bmatrix} \tag{5}$$

Here $\hat{E}$ is the reduced elastic modulus modified by the Poisson's ratio and is determined by Eq. 6.

$$\hat{E} = \frac{E}{(1-2\nu)(1+\nu)} \tag{6}$$

where τ and γ denote the normal stresses and shear stresses, respectively.

If temperature field is not evenly distributed in an engineering structure, thermal stresses can be induced due to different thermal expansion/contraction. Accordingly, the governing equations are modified and they are given as Eq. 7.

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{zx}\end{bmatrix}=\begin{bmatrix}\hat{E}(1-\nu) & \hat{E}\nu & \hat{E}\nu & 0 & 0 & 0\\ \hat{E}\nu & \hat{E}(1-\nu) & \hat{E}\nu & 0 & 0 & 0\\ \hat{E}\nu & \hat{E}\nu & \hat{E}(1-\nu) & 0 & 0 & 0\\ 0 & 0 & 0 & G & 0 & 0\\ 0 & 0 & 0 & 0 & G & 0\\ 0 & 0 & 0 & 0 & 0 & G\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{zx}\end{bmatrix}-\frac{E\alpha\Delta T}{1-2\nu}\begin{bmatrix}1\\1\\1\\0\\0\\0\end{bmatrix} \tag{7}$$

where α is the coefficient of thermal expansion (CTE). ΔT is the temperature change with respect to a base or reference temperature.

Cold worked beams have oriental texture microstructures and their mechanical behaviors are generally anisotropic [28]. Since the extension direction during cold-working process is largely along one direction, the governing equations for this case may be simply described as Eq. 8.

$$\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{Bmatrix}=\begin{bmatrix}S_{11} & S_{12} & S_{13} & 0 & 0 & 0\\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0\\ S_{13} & S_{23} & S_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & S_{66}\end{bmatrix}\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{Bmatrix} \tag{8}$$

And the non-zero elements (components) in the matrix S in Eq. 8 are:

$$\begin{aligned}
&S_{11}=\frac{1}{E_x}, \quad S_{12}=\frac{-\nu_{yx}}{E_y}, \quad S_{13}=\frac{-\nu_{zx}}{E_z}\\
&S_{21}=\frac{-\nu_{xy}}{E_x}, \quad S_{22}=\frac{1}{E_y}, \quad S_{23}=\frac{-\nu_{zy}}{E_z}\\
&S_{31}=\frac{-\nu_{xz}}{E_x}, \quad S_{32}=\frac{-\nu_{yz}}{E_y}, \quad S_{33}=\frac{1}{E_z}\\
&S_{44}=\frac{1}{G_{yz}}, \quad S_{55}=\frac{1}{G_{xz}}, \quad S_{66}=\frac{1}{G_{xy}}
\end{aligned} \tag{9}$$

Matrix *S*, the inverse matrix of the stiffness matrix, is also called the compliance matrix.

3.2.3. Problems of Flaws

The existence of flaws cannot be completely precluded in engineering structure. The flaws could come from design, e.g., the holes, or be introduced by manufacturing processes like welding and machining processes [25-26, 31]. The inclusions in the welding structures are generally treated as crack-like flaws. Therefore, for the case that the influence of flaws in the mechanical strength of the structures is concerned, fracture mechanics should be used to make mechanical analyses and reliability evaluation.

3.2.3.1. Hole Problems

For an infinite case of an elliptical hole loaded with a uniform stress σ in the *y*-direction shown in Figure 12, stresses in the vicinity of the elliptical hole can be analytically obtained. We take an example of the normal stress σ_{yy}, which is given as Eq. 10 [26-27, 30] and schematically shown in Figure 12. The solution reveals that the stress distribution near the hole is significantly uneven and the stress concentration at the location of the smallest radius ρ becomes infinite when the radius approaches zero.

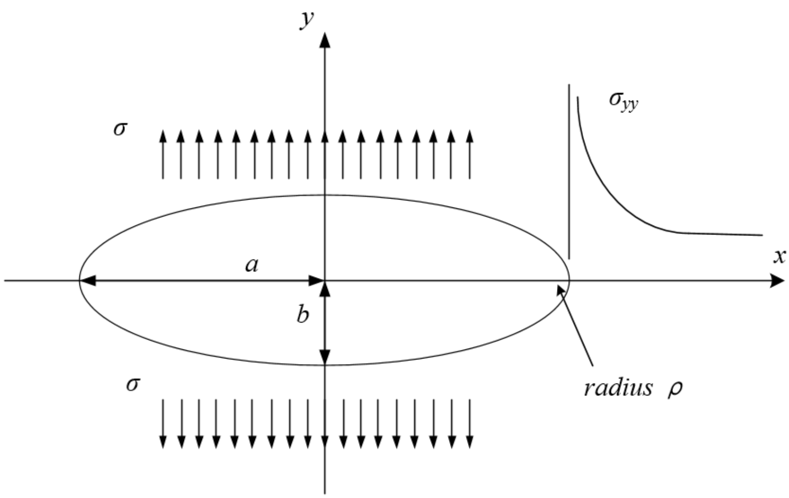


Figure 12. The elliptical hole problem.

$$\sigma_{yy}\left(x=a, y=0\right)=\sigma\left(1+2\frac{a}{b}\right)=\sigma\left(1+2\sqrt{a/\rho}\right)\approx 2\rho\left(a/\rho\right) \quad (10)$$

The stress concentration factor (SCF) K_t is:

$$K_t = 2\sqrt{a/\rho} \quad (11)$$

3.2.3.2. Typical Crack Problems

Hole problem reduces to crack problem when the radius ρ approaches zero and the stress concentration factor (SCF) becomes powerless to characterize the severity of the flaw. For crack problems, the analysis generally adopts the stress intensity approach [32].

Three basic loading modes, i.e., Modes I, II and III, for a cracked elastic solid is given in Figure 13.

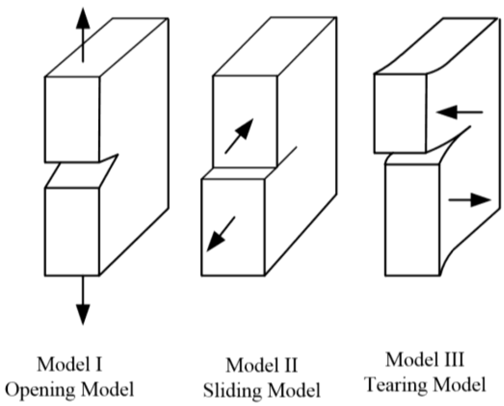


Figure 13. Fracture modes of crack problems.

The analytical opening-mode stresses are:

$$\begin{aligned}
\sigma_{xx} &= \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)+\dots \\
\sigma_{yy} &= \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)+\dots \\
\tau_{xy} &= \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\sin\frac{\theta}{2}\dots
\end{aligned} \quad (12)$$

The denominator factor $(2\pi r)^{-1/2}$ in Eq. 12 shows the singular nature of the stress distribution: stresses approaches infinity as the crack tip is approached, with a $r^{-1/2}$ dependency. So a new constant, the so-called stress intensity factor, SIF or K_I, is introduced in the stress field analysis. It is defined as the limit value shown in Eqs 13-15.

$$K_I = \lim_{r \to 0} \left(\sqrt{2\pi r}\, \sigma_{yy} |_{\theta=0} \right) \qquad \left[m^{\frac{1}{2}} MPa \right] \tag{13}$$

Similarly, the stress intensity factors K_{II} and K_{III} are:

$$K_{II} = \lim_{r \to 0} \left(\sqrt{2\pi r}\, \sigma_{xy} |_{\theta=0} \right) \qquad \left[m^{\frac{1}{2}} MPa \right] \tag{14}$$

$$K_{III} = \lim_{r \to 0} \left(\sqrt{2\pi r}\, \sigma_{zy} |_{\theta=0} \right) \qquad \left[m^{\frac{1}{2}} MPa \right] \tag{15}$$

A lot of flaws are surface cracks like scratches or shallow notches. And typical stress intensity factors (SIF) for surface crack problems, i.e., edge crack problems illustrated by Figures 14-15, are presented below. SIF for crack problems of the finite body can be numerically obtained. For edge crack problems, the mathematical expressions are given by Eqs 16-17.

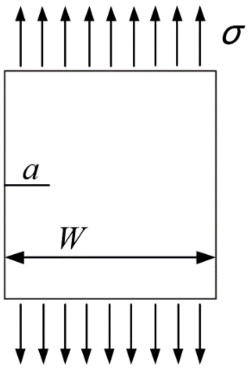


Figure 14. Edge crack problem.

$$K_I = \sigma\sqrt{a}\left[1.12\sqrt{\pi} - 0.41\frac{a}{W} + 18.7\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4\right] \tag{16}$$
$$\approx 1.12\sigma\sqrt{\pi a}$$

$$K_I = \sigma\sqrt{a}\left[1.12\sqrt{\pi} + 0.76\frac{a}{W} - 8.48\left(\frac{a}{W}\right)^2 + 27.36\left(\frac{a}{W}\right)^3\right] \tag{17}$$
$$\approx 1.12\sigma\sqrt{\pi a}$$

where a is the length of edge crack. And Eqs 16-17 are accurate when the value of $\frac{a}{W}$ is small enough.

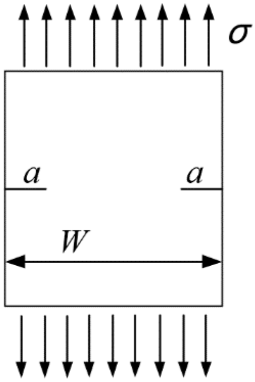


Figure 15. Double edge crack problem.

3.3. Evaluation Criteria for Flaw Problems

The critical value, which is defined as the fracture toughness and denoted as K_C, should be obtained from experimental measurements. A crack will grow when the crack tip stress exceeds a certain critical value [27] and the criteria for critical conditions are given as Eq.18. The stress intensity factor determines so called the amplitude of the crack tip stress for a certain geometry and loading case.

$$K_I = K_{IC} \ ; \ K_{II} = K_{IIC} \ ; \ K_{III} = K_{IIIC} \tag{18}$$

3.4. Database Development for Information of the Actual Situation

Mechanical tests and experiments are done for the study of mechanical behaviors of actual structures. And such results are further used to refine the numerical results. The actual loadings, which are the initial boundary conditions for numerical analyses, are also measured, determined and then input into the database. As shown in Figure 16, the approaches include the determination of the initial boundary condition, the numerical analyses, the diagnosis based on knowledge bases, the evaluation and the suggestion/ conclusion, the warning or alarming, and the refinement of models and new information input. Here multimedia systems involving the use of sound and video animation are adopted to improve communication and understanding.

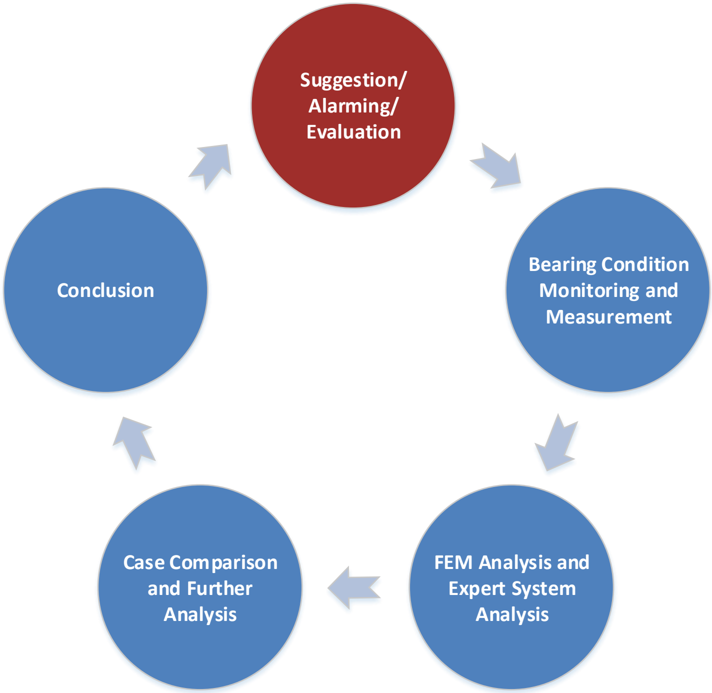


Figure 16. Principles for fault diagnosis and safety prediction.

3.5. Subsystems

3.5.1. Subsystem - Real Time Monitoring System

The real time monitoring system has the capability to collect the static stresses, the dynamic stresses, the strains, the wind speed in the gate tunnel, the forces for water gate opening and closing, and the data of parameters related to water flow.

3.5.2. Subsystem - Safety Management System

The architecture of safety management system is illustrated in Figure 17. Various sensors like the strain sensor, the vibration sensor and the temperature sensor are used to collect the mechanical conditions of the mechanical structures. For bearings, different surface or subsurface flaws lead to different vibration spectrum and different friction conditions, and thus different failure mechanisms, while the temperature change may change the rotation behavior of the bearing structure due to the deformation of the whole structure and the physical property change of the lubrication oil film. The evolution of the flaws results in the change of vibration spectrum. The data collected by the sensors are analyzed by industrial PCs (IPC) and the results act as the input information for further numerical analyses. Together with the mathematical models and expert systems, safety evaluation is done on servers and the results can be displayed on big screens or inquired by users.

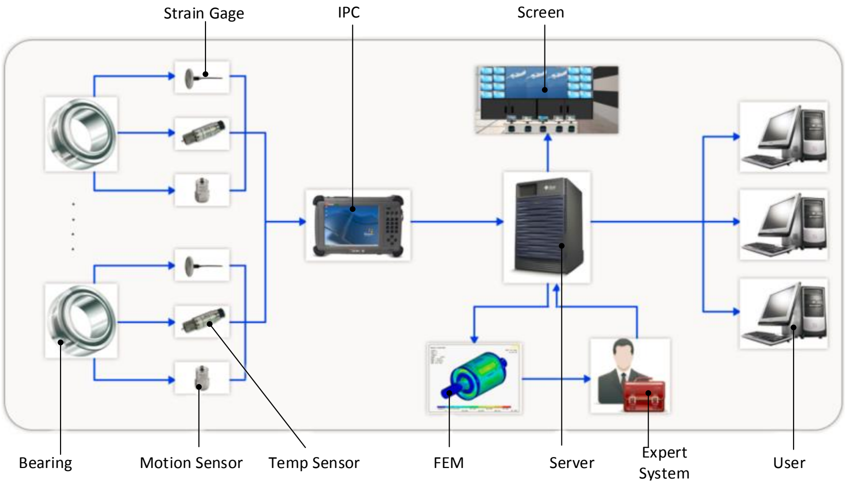


Figure 17. Architecture of safety management system for water gate system.

3.6. Methodology for the Realization of Real Time Measurement

Real time monitoring of the change of stresses and deformation can greatly help warn potential accidents, wrong operations and alarm human operators or monitors, and help evaluate the extent of damage to the mechanical structures.

3.6.1. Real Time Stress Measurement

Strain gages are fixed on the mechanical structures of the water gate, i.e., the opening/closing components. The positions for the strain gages are determined by the results of the experimental tests and numerical simulations. In this way, useful strain data can be obtained *via* a series of data collection and rationalization processes like the signal amplification and filtering. The stresses can be further calculated using the theory of elasticity. An example is presented here to show the locations where the single strain gage and the strain gage rosette (as shown in Figures 19-21) are positioned.

The three dimensional (3D) drawing of the opening/closing structures is shown in Figure 18. Two dimensional (2D) sketches of the upper-beam structure, lower-beam structure and the arc plate are given in Figures 19-23, respectively.

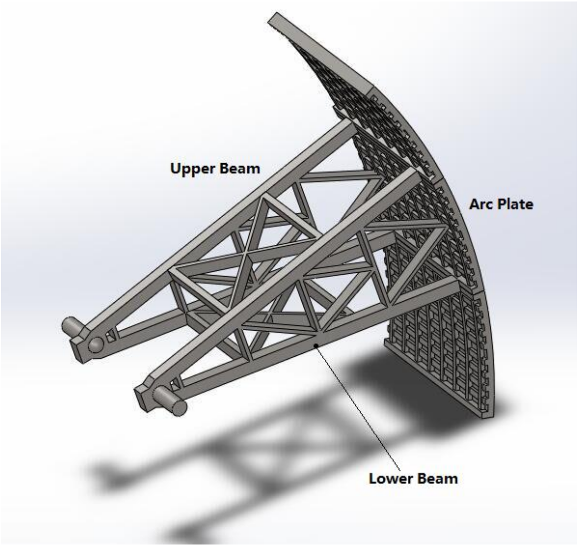


Figure 18. 3D plot of the mechanical structure of water gate system.

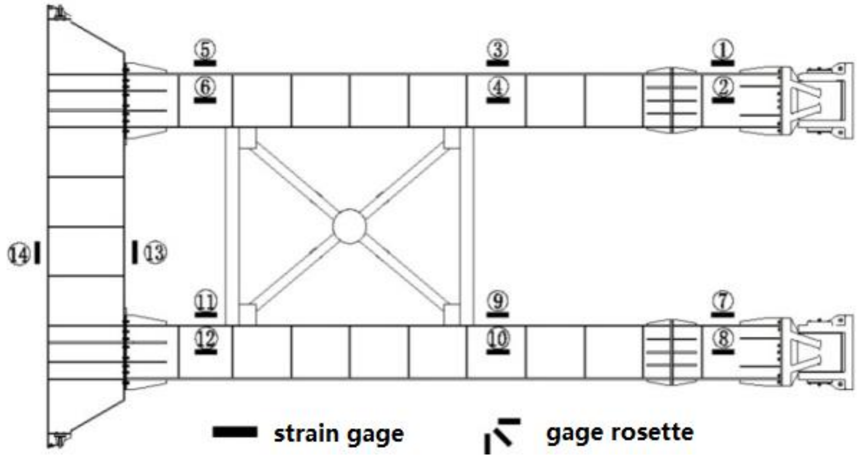


Figure 19. Measurement locations on upper beams.

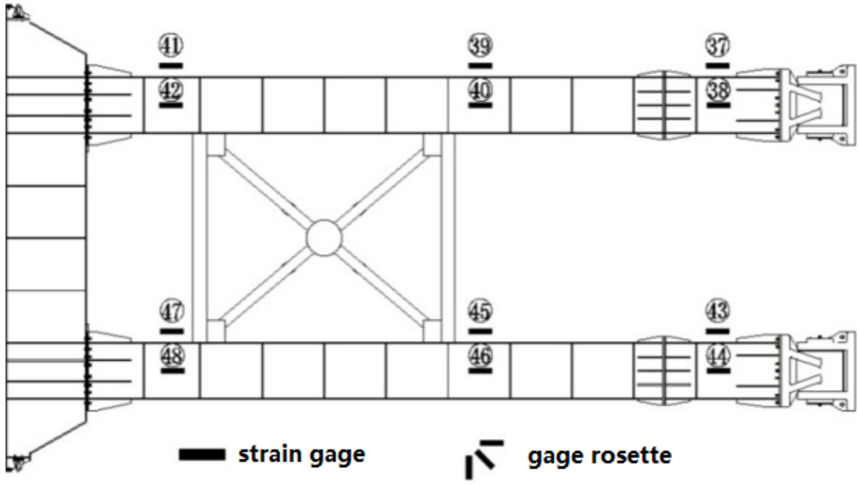


Figure 20. Measurement locations on lower beams.

3.6.2. Real Time Deformation Measurement

For a mechanical structure with large sizes, the local deformation could be big even if the loading is relatively small and the stress is well below the yield strength of the material. Therefore, the deformation measurement should also be taken into account for the reliable evaluation.

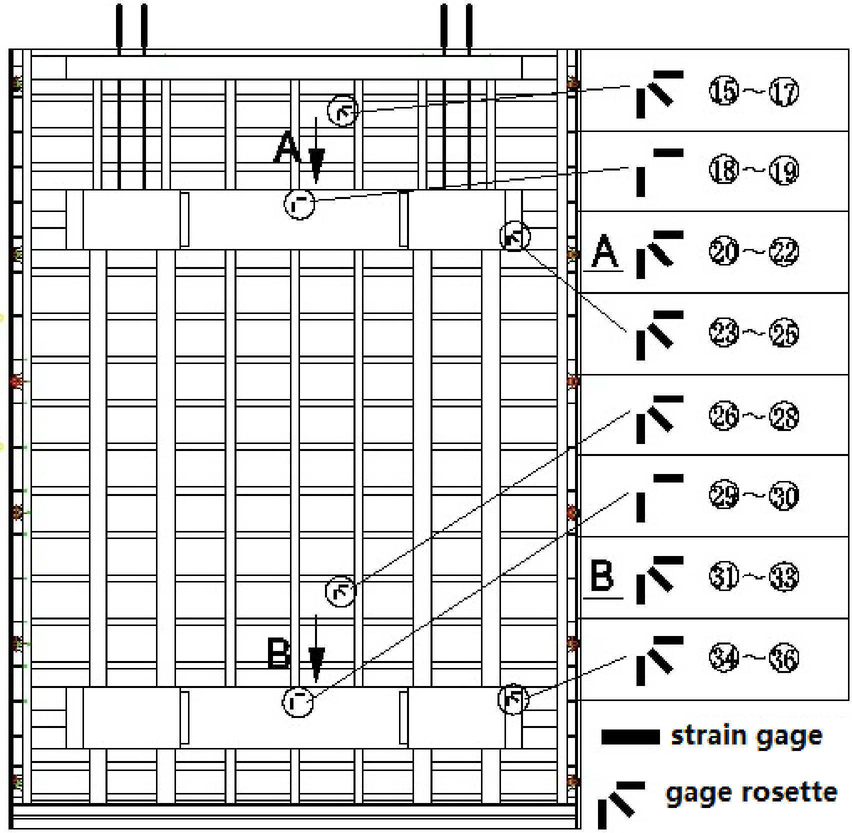


Figure 21. Measurement locations on back surface of arc plate.

Specific marks have been made on the back surface of the arc plate, and the upper and bottom beams as well. And the distance change between two marking points can be used to determine the deformation. Industrial cameras are used here with the night vision function to realize the deformation measurement under both the static and the dynamic conditions. The application of multi-vision technology aims at capturing the spatial traces of the marking spots. Combination with the strain measurement, the whole mechanical situations of the water gate system subjected to various mechanical loadings like the body weight, the hydraulic pressure, the disturbance of water flow can be obtained.

The locations of the marks are, respectively, shown in Figures 22 and 23.

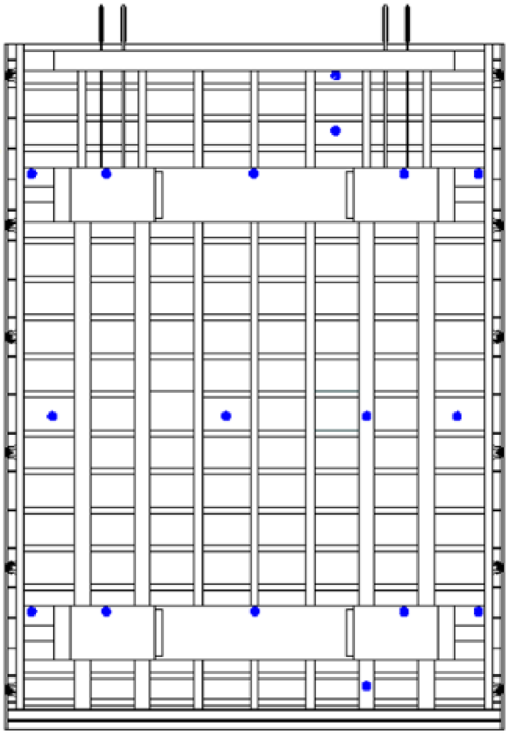


Figure 22. Marking points on the arc plate.

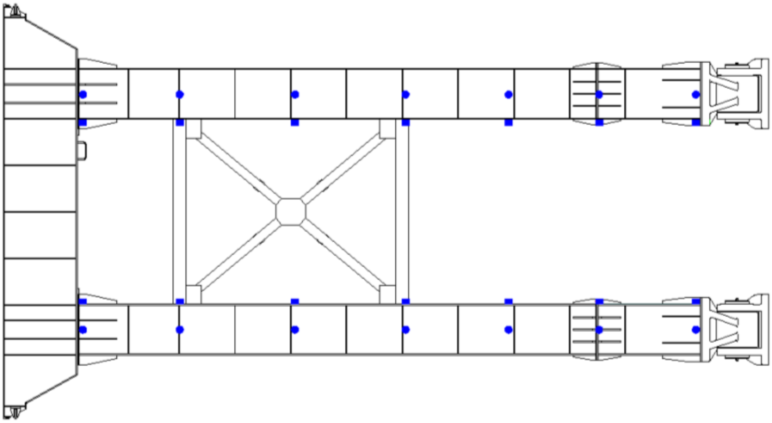


Figure 23. Marking points on the beams.

3.6.3 Real Time Acceleration Measurement

The acceleration sensors are installed into the opening/closing mechanical structures to measure the vibration characteristics during the operations. The locations of the sensors are as shown in Figures 24-26.

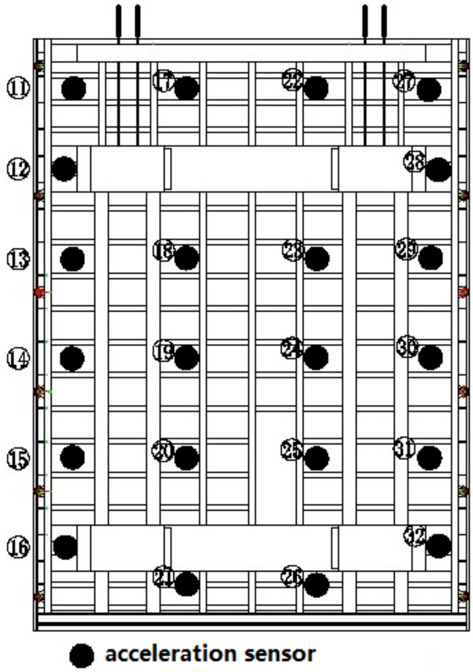


Figure 24. Locations for acceleration sensors on arc plate.

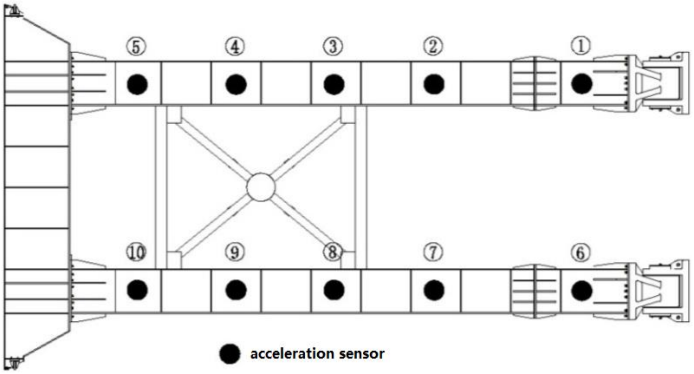


Figure 25. Locations for acceleration sensors on upper beams.

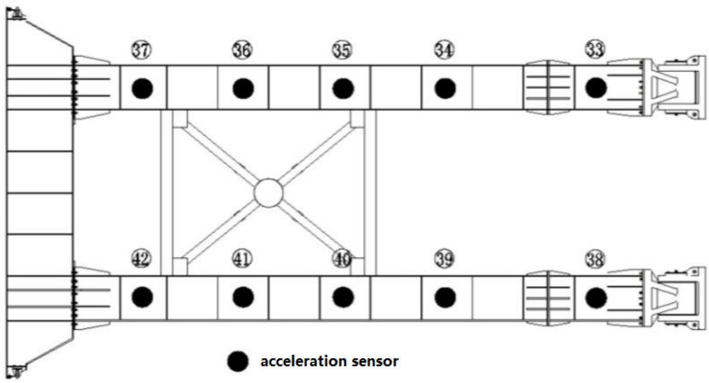


Figure 26. Locations for acceleration sensors on lower beams.

3.6.4. Real Time Force Measurement for the Opening/Closing Operations

Three types of sensors, the strain gages, the photo eyes and the float type transmitters, are used to measure the strains, the change of water level, and the time when the water gate starts opening or when it is just closed. So the strain change during the whole operating processes can be collected as well as the change of water flow and pressure parameters. Hydraulic components (see Figure 28) generally get involved in the operation. The stresses can be calculated using the measured strains.

Strain gages are located as shown in Figures 27 and 28.

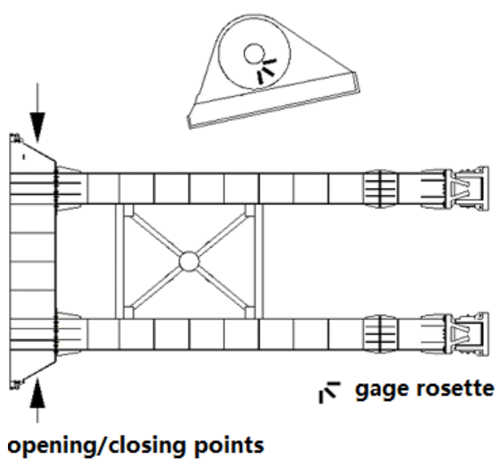


Figure 27. Measurement points for the opening/closing components.

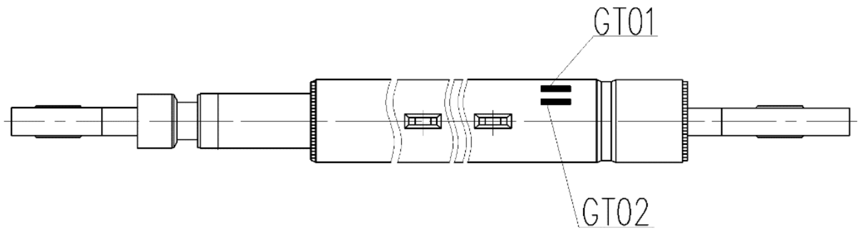


Figure 28. Strain and deformation measurement for hydraulic component.

3.7. Architecture of WRFS System

The entire system is based on the IoT technology. As shown in Figure 29, the architecture consists of the field layer, the networking layer and the application layer.

3.7.1. Field layer

Field layer is responsible for the information collection and data generation. The hardwares of the field layer include a lot of sensors and industrial cameras as listed in Figure 20. The fundamental data for a series of physical parameters are collected and primarily processed in this layer.

3.7.2. Networking layer

Most computations are performed on the servers or the cloud platform to ensure the quick prediction and the real time monitoring and alarming.

3.7.3. Application layer

This layer provides the customers with the services listed in Figure 29.

3.8. Application of WRFS System

The WRFS system has been applied in the Xiaowan Power Station. The front side of the station faces the reservoir formed by the dam on the Lanchang River. The photo of the power station is given in Figure 30 to present the detailed structures of the hydraulic engineering. This hydraulic engineering is categorized as first-tier one according to the national standards of mainland China. Its dam has a height of 294.5 meters high.

WRFS system was put into use in the Xiaowan Power Station in 2009 and has been in service since then.

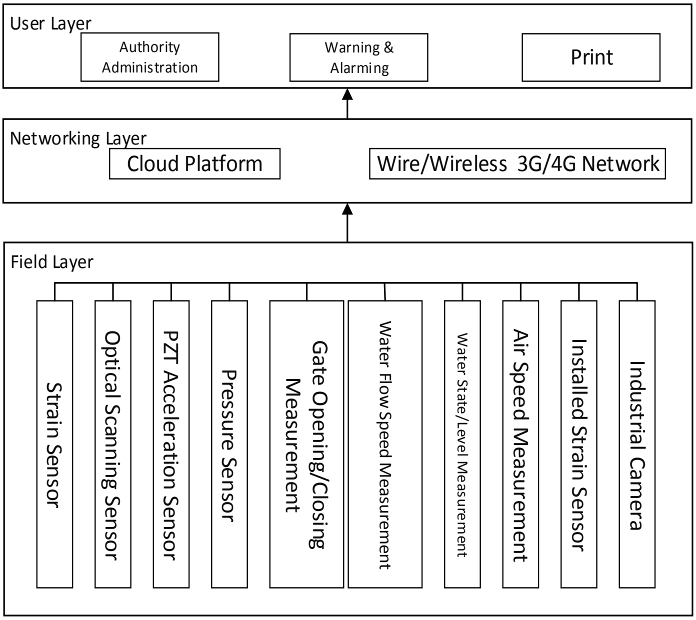


Figure 29. System architecture.

Figure 30. The front side of Xiaowan Power Station.

4. WATER SAFETY MANAGEMENT SYSTEM FOR RURAL AREAS IN MAINLAND CHINA

4.1. Background

Water resource shortage in rural areas is a serious problem due to either the shortage of water or the contamination of surface or subsurface water resources. Serial annual reports by the Ministry of Water Resources have just presented a dire picture for the state of water resources in mainland China after continuous investigation [1, 43-44]. In rural areas, people routinely use the subsurface water which is pumped out to the water plants for water treatment and then transferred to the end users, i.e., the villagers or residents in small towns [1]. Unlike the subsurface water of three decades ago, today's subsurface water quality varies a lot and cannot be taken for granted owing to various pollutions. Pollutants could be either organic or inorganic chemicals. In the developing regions (usually rural areas), due to inadequate water treatment facilities, high incidences of disease and mortality caused by drinking contaminated water just occur. For rural areas, typical pollutants could be fecal matter, toxic compounds like ammonia, pesticides and even some industrial effluents [34-36], and bacteria or sewage fungus. And usually chlorine gas (Cl_2) is pumped into the water to eliminate the pathogenic bacteria. In order to better manage the water resource and monitor the water quality in the rural areas, the Ministry of Water Resources has set the rules and policies that support, guide and promote the movement of digital water resources. The movement serves the purpose for reliable information on water resources and quick response if the drinking water quality is compromised. Clearly, the water management system has to be developed to help collect detailed information on the hygiene conditions of drinking water, help allocate water resources in a comprehensive manner, and satisfy the basic water demand for human and livestock efficiently.

4.2. Detection or Measurement Methods

The detection or measurement methods are for the water quality monitoring and the fault detection of pipes or tunnels for water transportation.

4.2.1. Biochemical Oxygen (O_2) demand (BOD) or Chemical Oxygen Demand (COD) Tests

In practice, the concentration of dissolved oxygen (DO) is used to indicate the health state of a water source. As shown in Figure 31, oxygen solubility in pure water is the function of temperature. Clearly, clean water without any content or very little biodegradable pollutants has an oxygen concentration of about 9–10 mg per liter when it is in equilibrium with the air within the temperature range of 20 to 25 degree centigrade. And the oxygen concentration in clean water is temperature dependent and the concentration decreases as temperature rises.

BOD measurement is to measure the quantity of oxygen required by these organisms to break down a given quantity of organic waste. Since the BOD test measures only the biodegradable material, it may not give an accurate assessment of the total quantity of oxidizable material in a sample in the circumstances where the presence of toxic substances may subdue the activities of the oxidizing bacteria. In addition, measuring the BOD typically takes long time, usually more than five days [35]. The chemical oxygen demand (COD) test measures the total oxygen demand. It is a measure of the total amount of oxygen required to stabilize all the waste. Compared with BOD, COD is a quicker measurement method.

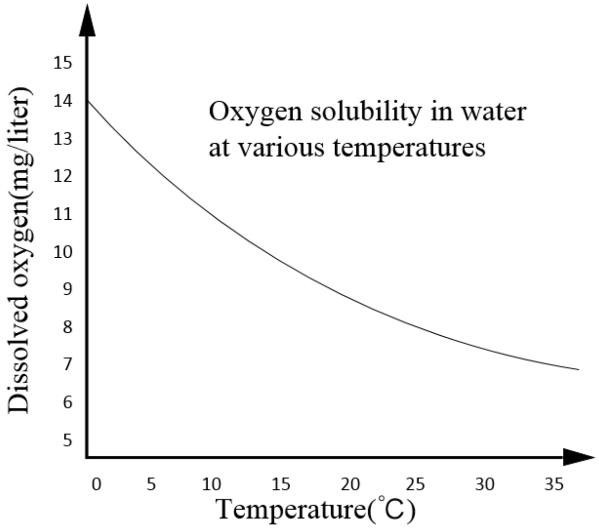


Figure 31. Effects of temperature on oxygen solubility in pure water.

4.2.2. Measurement of Escherichia Coliform Bacteria

Pathogenic microorganisms may pose a significant risk to human health [37]. Escherichia Coliform (E. coli) bacteria are the most common fecal indicators. And their measurement is widely used throughout the world to test if fecal contamination of water samples has taken places.

4.3. Measurement of the Parameters of Water Flow in Pipes

Water distribution systems in rural areas include pumping stations, water storage and distribution piping networks. Pumping stations can pump water out of the wells or deliver water from water storage/water plant to the end users/customers. And the water distribution is routinely made *via* the networks of pipelines. By measuring the parameters related to the water flow in the pipes, not only can the volume of delivered water be calculated, but also possible water leakage can be detected. For example, for the case that the pumps get involved in the water distribution system, which means that extra energy from the pump is input to increase the water pressure, the energy components along a pressure pipe shown in Figure 32 can be described as:

$$\left[p/\gamma + Z + V^2/2g + H_G\right]_{\text{site}\,m} = \left[p/\gamma + Z + V^2/2g + H_L\right]_{\text{site}\,n} \tag{19}$$

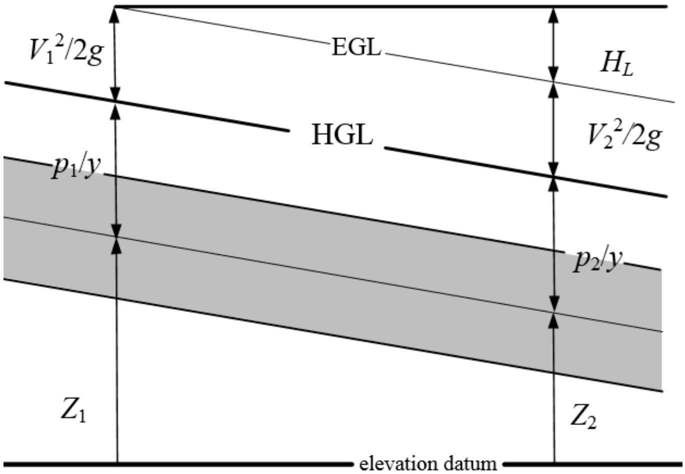


Figure 32. Energy components along pipe with extra energy input.

The parameters p and γ are the pressure and the specific weight, respectively. Z is the elevation above some base elevation, V is the velocity, and g is the gravitational acceleration.

Letters m and n in Eq. 19 are used to describe the numbers of the site points of interests.

EGL, HGL and H_L in Figure 32 are for the energy grade line, the hydraulic grade line, and the head loss, respectively.

Friction is the main cause of water head loss. Chezy's or Kutter's equation, Hazen–Williams equation, and Darcy–Weisbach or Colebrook–White equations are used for pressured pipe flow case [39-40]. In those equations, flow velocity, V, is defined as an empirical function of a flow resistance factor, C, the hydraulic radius (cross-sectional area divided by wetted perimeter), R, and the friction or energy slope, $S = H_L / Length$ [39-40].

$$V = k\,C\,R^x\,S^y \tag{20}$$

The terms k, x and y in Eq.20 are parameters. The roughness of the flow channel (pipe), the channel (pipe) shape, the depth and fluid velocity all play the roles in the determination of the flow resistance or roughness factor, C. Values of C for different types of pipes are listed in hydraulics handbooks or textbooks [39-40].

4.4. System Architecture

The system architecture is shown in Figure 33. Apparatus of the field layer include the industrial cameras, the chlorine detectors, and the pressure sensors and flowmeters for the measurement of parameters of the main pipelines. Data and video files are analyzed by industrial PCs (IPC) and server, respectively. The analysis and measurement results can be inquired by users or displayed on the big screen. Data collected by the pressure sensors and the flowmeters for the pipelines of end users are transmitted *via* wireless communication networks.

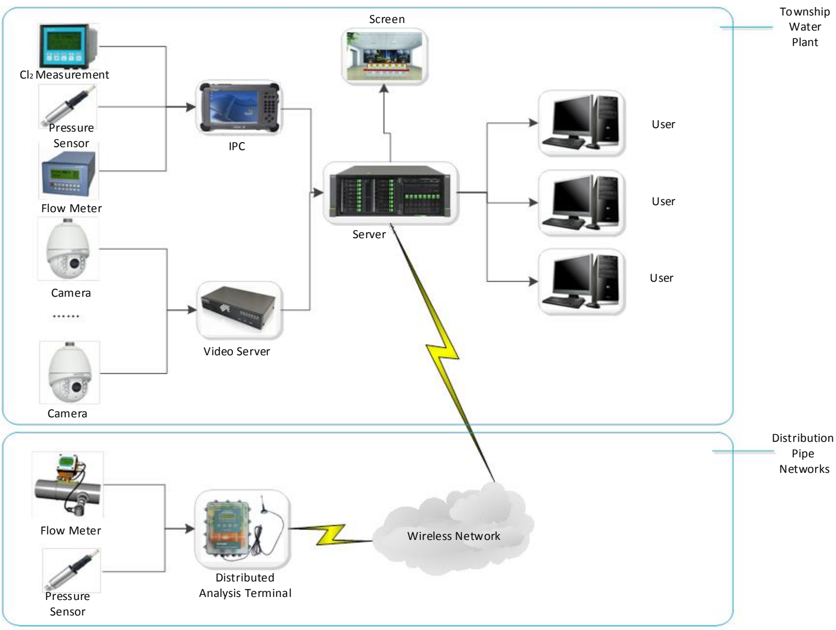


Figure 33. System architectures for water management in rural areas.

4.5. Main Functions

Main functions of the system have:

a) Real time measurement of water pressure and the rate of water flow;
b) Real time monitoring the electric voltage and electric current of the pump motor;
c) Remote control of the pump operation;
d) Real time measurement of the speeds of the inflow and outflow of the water in the water plant;
e) Online monitoring the water quality and the change of the water surface level in the water plant;
f) Real time monitoring the operation of pumps used to pump chlorine gas into the water for chlorination process;
g) Real time monitoring the operation of pumps used to pressure the water to the end users from the water plant;
h) Real time monitoring the conditions of power substations in the water plants.

5. INSPECTION SYSTEM FOR HYDRAULIC ENGINEERING

According to mainland China's law, the inspection of hydraulic engineering is under the jurisdiction of the Ministry of Water Resources. Besides the inspection of the engineering quality, the inspection also includes the audit of the capital investment, the safety management during the engineering project construction and so on. Obviously, the whole contents concerning the hydraulic engineering inspection are complicated, sophisticate and usually time consuming. Huge information needs to be collected and analyzed to complete the evaluation and grading processes, to realize efficient and reliable audit, and to make inspector management more rationally. Aiming at overcoming the current difficulties, a system has been developed for the inspection of hydraulic engineering. The architecture of the inspection system for hydraulic engineering is given in Figure 34.

Inspection group consists of experts, specialists and staffs. Group members may be selected from different working units by the agencies of the Ministry of Water Resources of China. Statistical analysis module in Figure 34 is responsible for grading the inspector and the evaluation of the inspected hydraulic engineering. Inspection guidelines, rules and laws are also included in the inspection system to help and guide the inspectors.

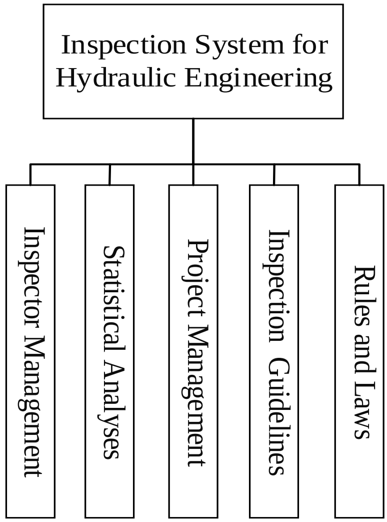


Figure 34. Inspection system architecture.

5.1. Main Functions of Inspection System

The inspection information and relevant data are stored in databases and can be inquired by officials of government agencies. The fact that the system can present and provide the statistical analysis results greatly enhances the efficiency of inspection activities.

The functions of data and information input are shown in Figure 35 while the functions for information inquiry are given in Figure 36.

The inspection system can also handle the capital investment audit and mismanagement check. The functions for the capital investment audit and analysis are shown in Figures 37-38, while mismanagement affairs and any unauthorized deviations from the previous plan are documented and archived.

5.2. Inspector Management Functions

Inspectors may carry out the inspection activities all over the mainland China and good inspector management is necessary for good inspection management. The principles for inspector management are:

a) Inspector’s application for the inspection of specific hydraulic engineering is factored;
b) An inspector can not inspect three hydraulic engineering projects in one province successively;
c) Inspectors ranking in the top tier are preferred for inspection;
d) Inspection group shall consist of both senior inspector(s) and the freshmen;
e) Inspectors cannot be overloaded by too many inspections in a certain time period;
f) Specialists should be included in the inspection group for specific audit or check;

Following up these principles, the inspector management system can suggest appropriate inspection group. An example is shown in Figure 39. The information on names and working units is deliberately blackened in Figure 39 for privacy concerns.

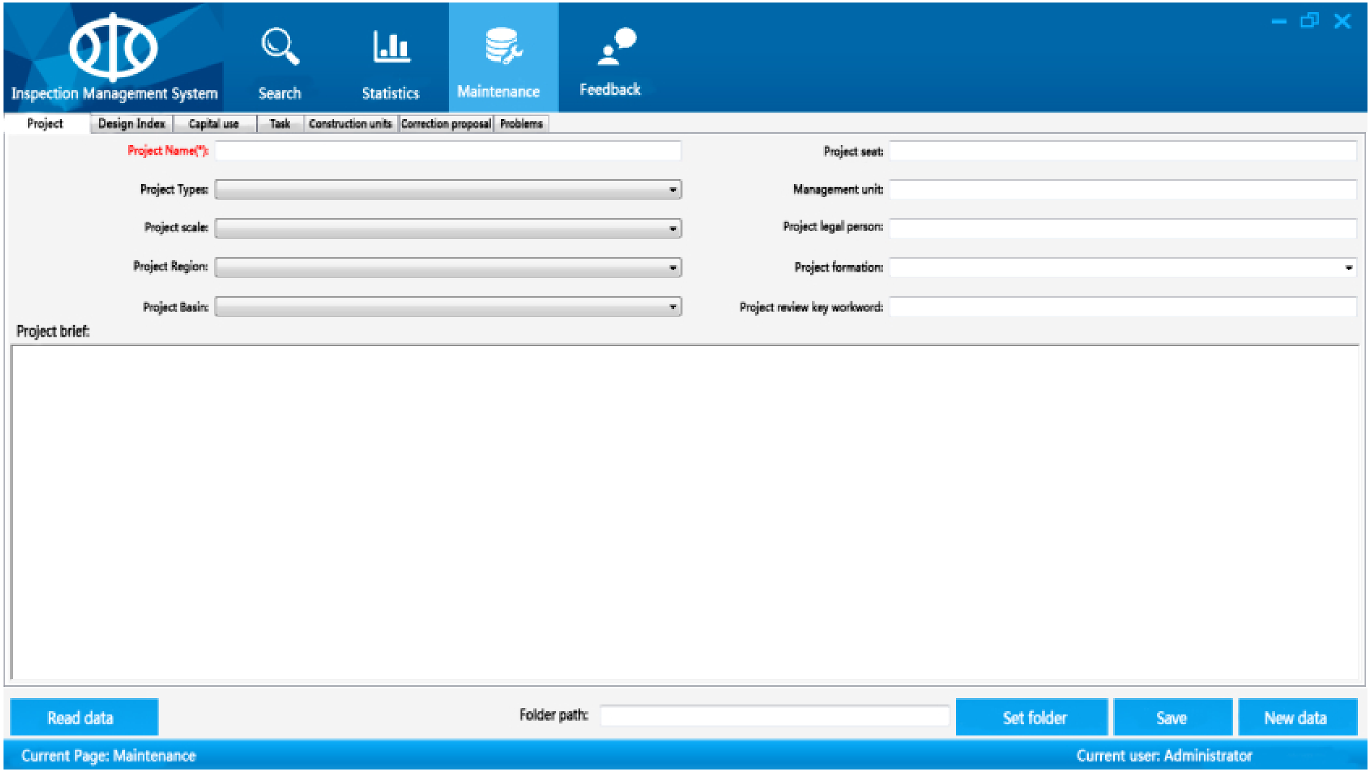


Figure 35. Data and information input.

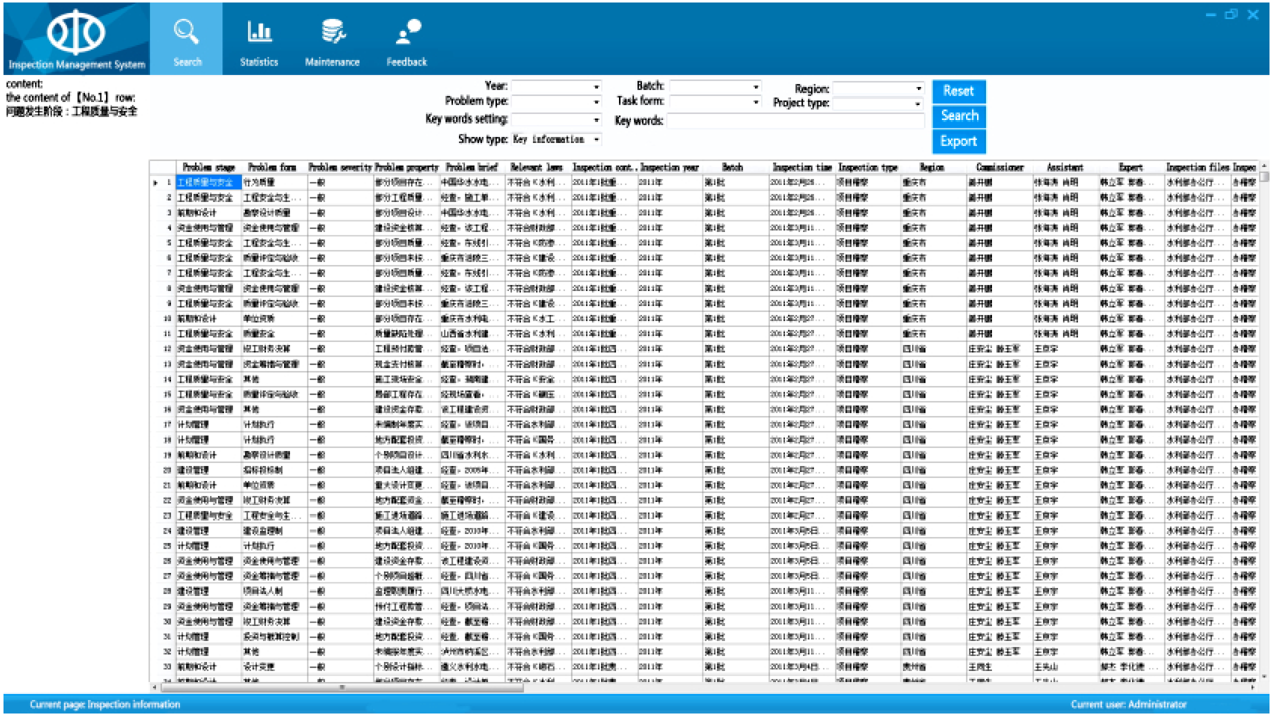


Figure 36. Inquiry of inspection information.

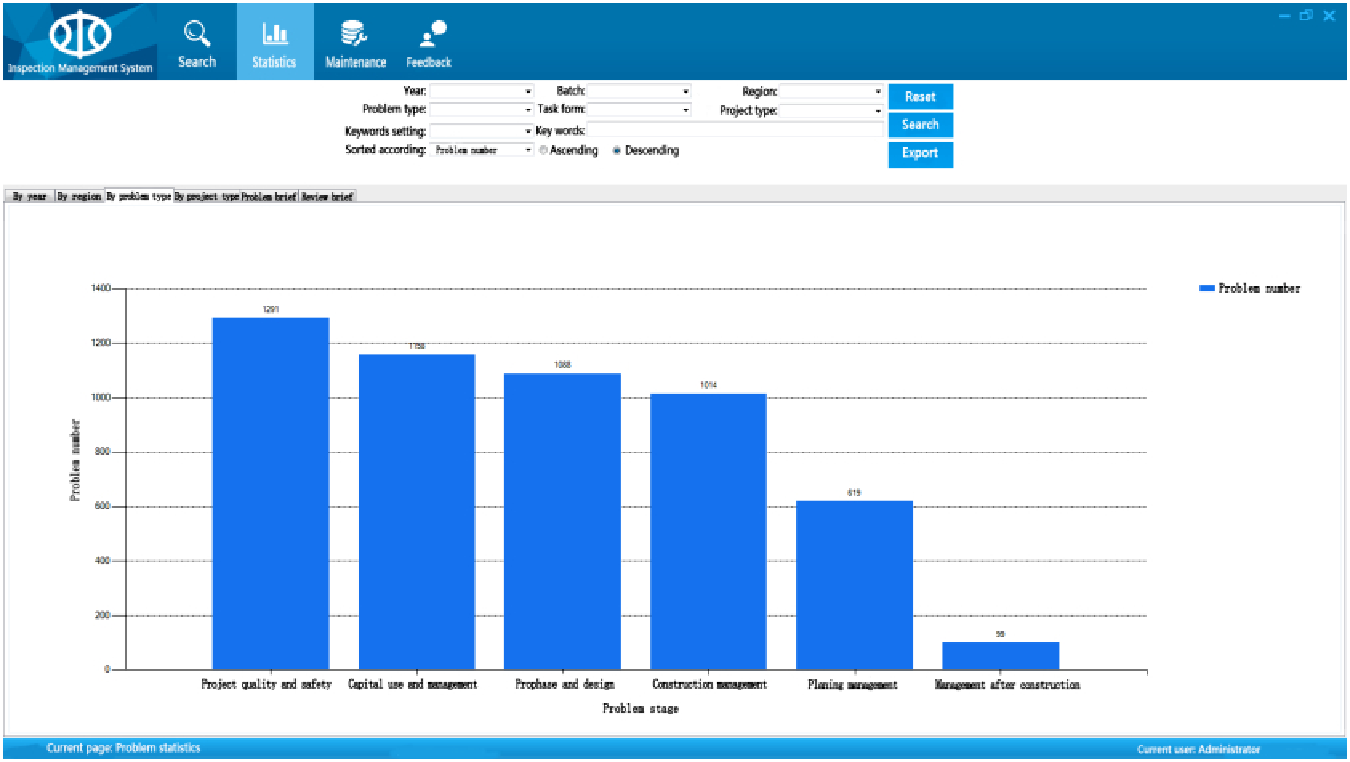


Figure 37. Mismanagement analysis.

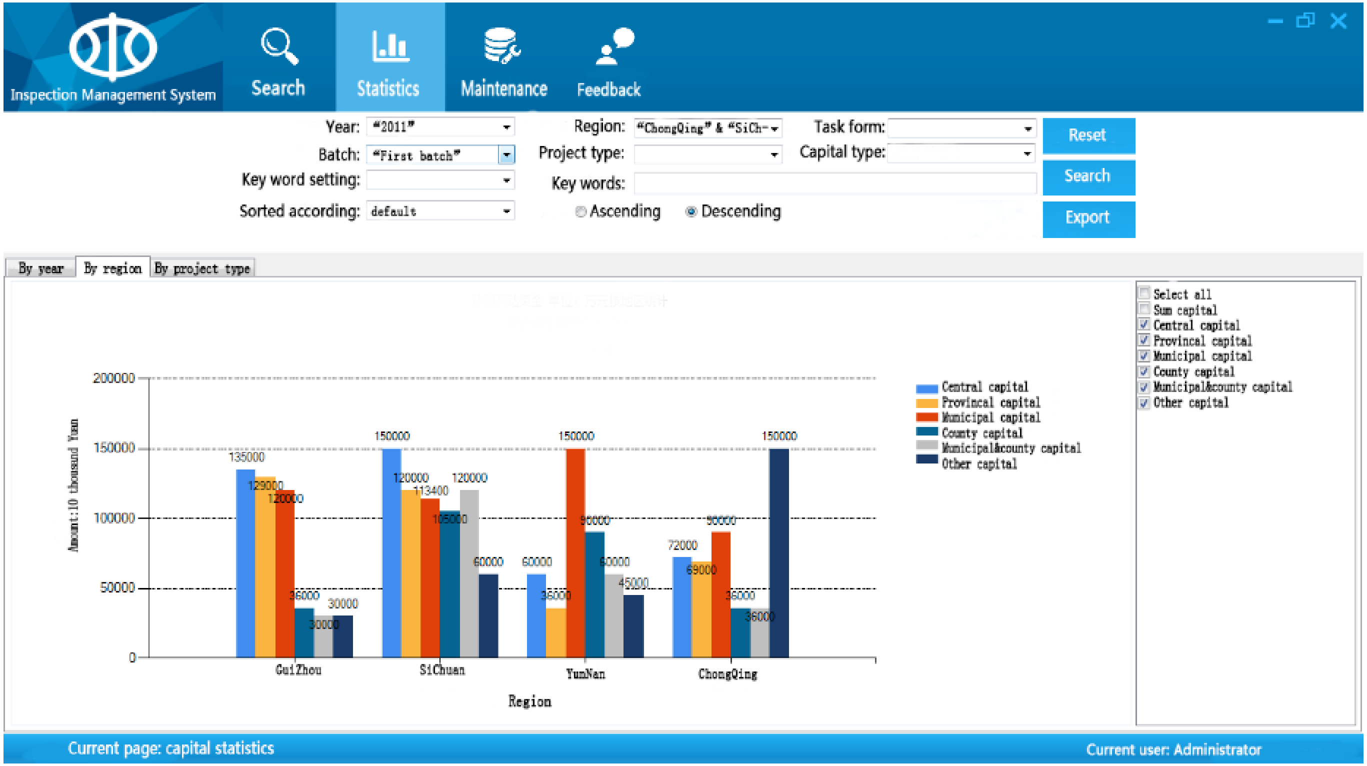


Figure 38. Capital investment audit and analysis.

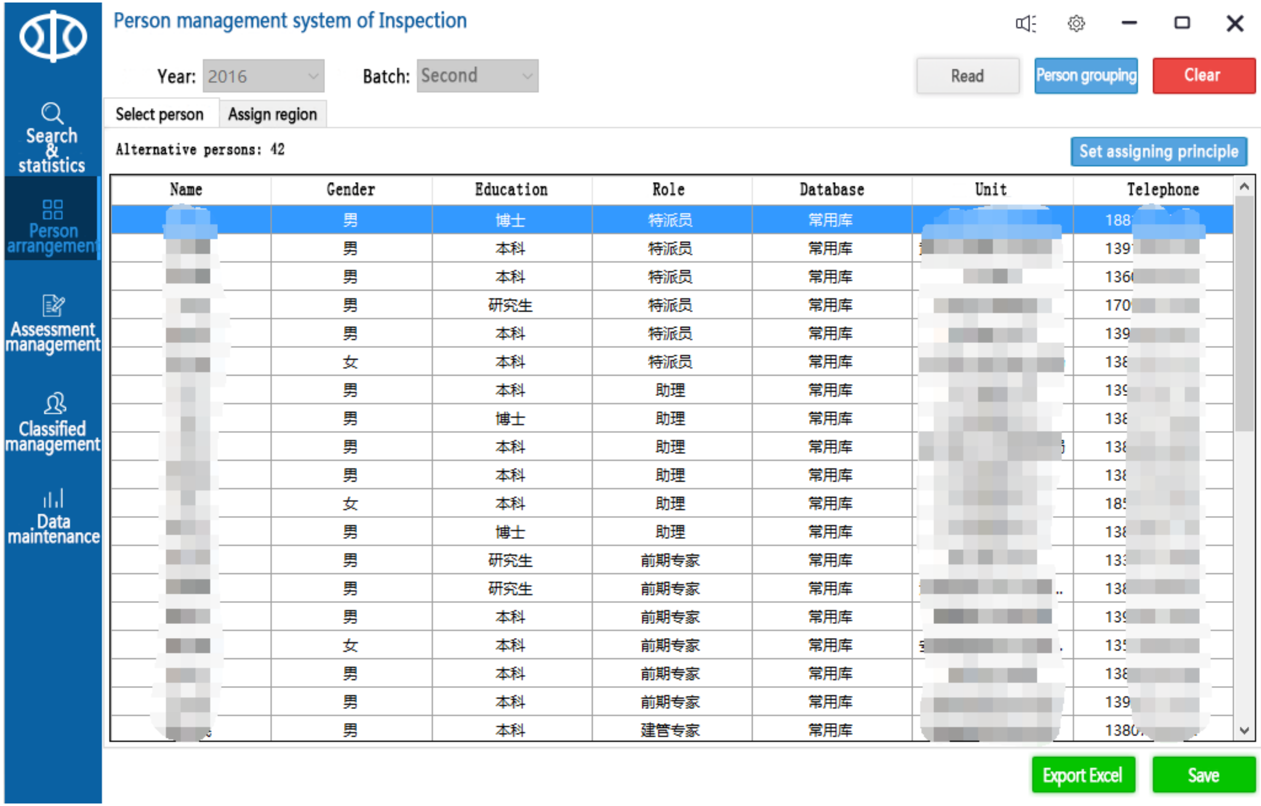


Figure 39. Inspector management system.

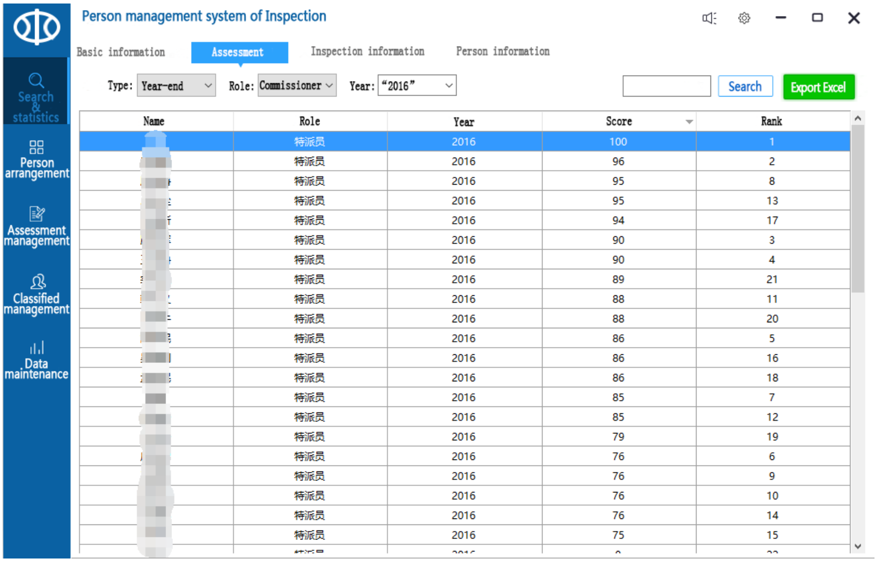


Figure 40. Inspector evaluation and ranking.

Inspector evaluation function can quantitatively evaluate each inspector. An example is shown in Figure 40. Similarly, here the private information is blotted out in the figure above.

CONCLUSION

Greatly improved computation capability and data storage, modern information technology as well as the quick and reliable communication methods all contribute the development of modern water resources management systems. The situation of water resource now is extremely severe owing to the shortage of water resources, the water pollution caused by the rapid economic development, and the lack of comprehensive water resource management system. Clearly, the comprehensive water management is essential to overcome the challenge and to ensure the further development for mainland China. In this chapter, based on modern technologies, particularly information technologies (IT), four systems related to water resources management have been developed aiming at securing the comprehensive utilization of water resources, the mitigation of disasters like floods or droughts, drinking water safety monitoring and so on. The algorithms as well as the approaches/methodologies are also introduced in the study. These four systems for water resources management have been put into use.

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Chapter 2

GROUNDWATER MANAGEMENT IN THE REGION OF LA PLATA, PROVINCE OF BUENOS AIRES, ARGENTINA

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ABSTRACT

The paper describes actions applied to the management of water resources in the region of La Plata (Buenos Aires Province, Argentina). The overexploitation of groundwater has modified the hydraulic conditions and, at the same time, has affected the hydrochemical characteristics by favoring contamination from human wastes. At present, the average exploited groundwater volume for human consumption is 73 hm^3/y and since a substantial increase of demand for water is predicted in

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future years, sustainable groundwater exploitation becomes essential. Rational management is necessary to reach a balance between water demands and groundwater conservation to avoid the extreme deterioration of water quality.

Keywords: groundwater management, Buenos Aires Province (Argentina), water balance, hydrologic modification

INTRODUCTION

Groundwater exploitation in La Plata started in 1885 to meet the needs of an increasing population. Through the years, the intense exploitation imposed a hydraulic regime characterized by depression cones in constant expansion that modified natural hydraulic gradients. The original flow direction of groundwater discharge towards the Rio de la Plata became altered, with a subsequent inversion of flow direction that caused salt water intrusion into the producing area.

As a result, in 1945 some exploitation wells had to be abandoned because of their increasing salinity. To compensate this loss and to keep pace with demand, in 1955 the drinking water supply was reinforced with fresh water from the Rio de la Plata, delivered to the city through a 9 km long pipe. At present, water supply is provided jointly from surface water and groundwater.

There is, however, a need for adopting reviewed techniques of groundwater management in agreement with the current demands. Problems derived from depletion of groundwater reserves tend to be solved with the increase, conservation and relocation of drinking water sources (Konikov and Kendy, 2005). However, such management policies have to be considered in a scenario of sustainable groundwater exploitation based on the quantification of the hydrological balance on a basin scale (Kalf and Wooley, 2005). Moreover, problems of water quality, pumping economy, ecological constraints and social and environmental effects of overexploitation should also be accounted for (Custodio, 2002).

This chapter aims to analyse the hydrological conditions in the region of La Plata, and recommends management methods for sustainable groundwater exploitation.

STUDY AREA

The city of La Plata, located to the northeast of the Buenos Aires Province, was founded in 1882 (Figure 1). Urbanized, industrial and rural zones coexist in its area of influence. The population of La Plata is now over 687 000. There are about 1000 manufacturing industries related to food, metal, and automotive (Figure 2).

The city area spreads over the Arroyo del Gato (literally, Cat's creek) basin with a drainage network altered with canals, rectifications, culverting, etc. The upper Arroyo del Gato basin has developed into a suburban zone with low population density where the primary economic activities are horticulture and floriculture, with a few industries. In the mid creek basin there is a significant increase in urbanization and population density, in addition to a larger number of industries, service activities and districts of precarious housing settled next to the stream. In the lower creek basin the watercourse crosses a low population density zone (Varela et al, 2002).

Geomorfologically, the study area is a typical flatland (topographic slope 0.1%) with its drainage basin developed between 0 and 25 meters above MWL (mean water level of the Rio de la Plata). The average discharge is 0.08 m^3/s. Two morphologic units (Figure 3) are clearly defined: the inland zone and the coastal plain (Fidalgo and Martinez, 1983). The interior zone extends between 5 and 25 m above MWL, where soils are well drained and infiltration processes predominate. The coastal plain is below 5 m above MWL and constitutes a zone of partial discharge of the groundwater system.

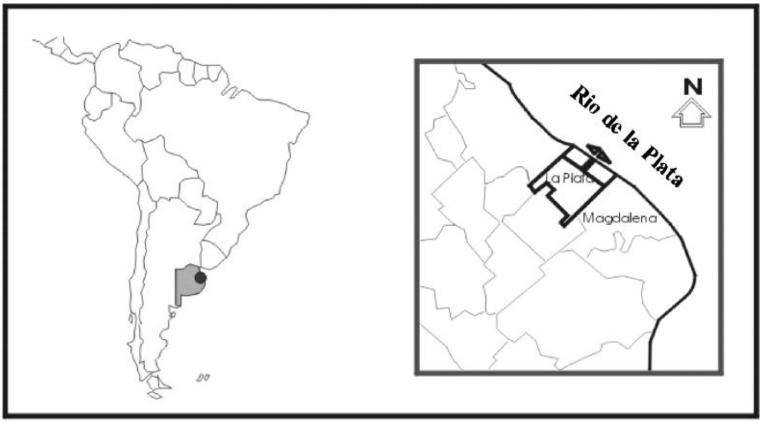

Figure 1. Study area.

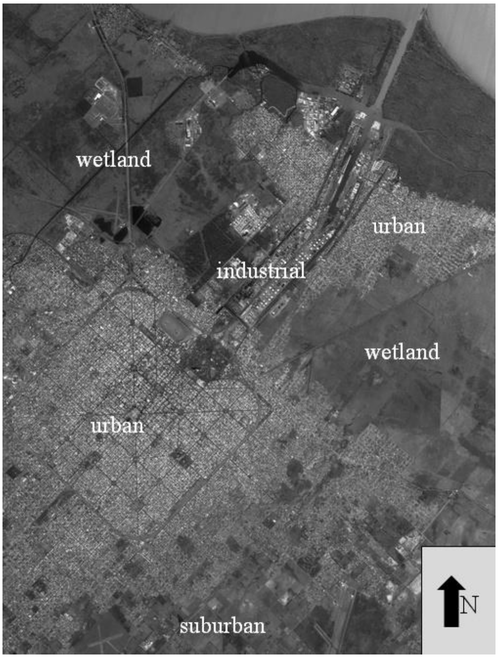

Figure 2. Land uses of the Arroyo del Gato Basin.

Figure 3. Morphologic units.

GENERAL HYDROGEOLOGY

Hydrogeologically, there exist two units of practical importance: Puelches Formation (sands) and Pampeano Formation (loess, sand, silt and clays) (Figure 4). These units have alternating water producing sections separated by sediments of low permeability, all of them forming a multilayer aquifer. The upper aquifer known as Pampeano (Pampian) is composed of silts with subordinate sands and clays, with a thickness of around 50 m and a transmissivity of 200 m^2/d. The Pampeano includes the water table at a depth varying between 5 and 10 m under natural conditions. The Puelches sands underlie the Pampeano Fm and represent the most important aquifer in the northeast of the Province of Buenos Aires; they are composed of a sequence of fine to medium quartz sands with approximately 20 m in thickness and a transmissivity of 500 m^2/d (Auge, 1995, 2005). The regional recharge of the Pampeano is of meteoric origin, whereas the Puelche aquifer is indirectly recharged by the Pampeano through downward vertical filtration (Sala and Auge, 1973). Local groundwater discharges into the main streams, whereas regional groundwater discharges into the Rio de la Plata (Laurencena et al, 1999).

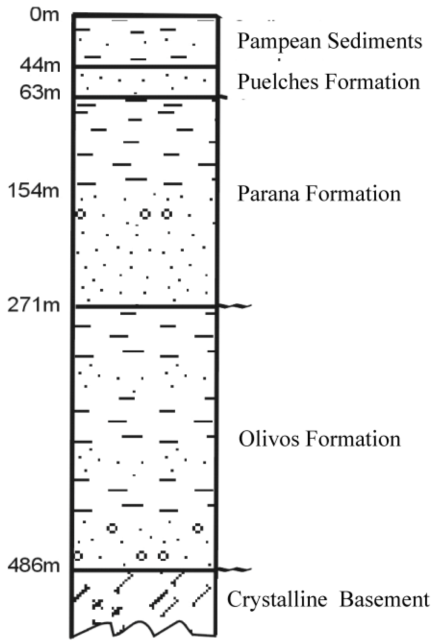

Figure 4. Stratigraphic column of the study area.

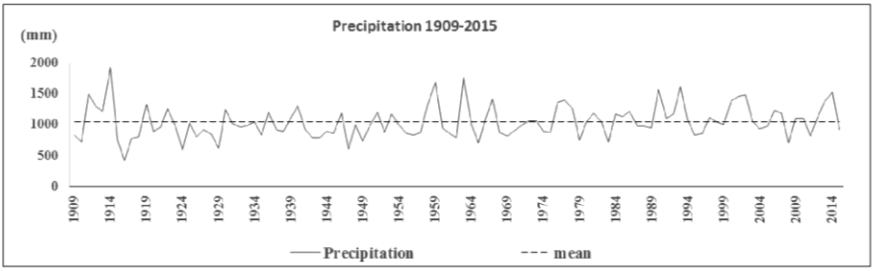

Figure 5. Typical annual precipitation of the La Plata (1909 – 2015). The dash line represents the mean precipitation.

HYDROLOGIC CHARACTERISTICS

The region is characterized by its climatic homogeneity. The annual precipitation shows alternating dry and humid periods (Figure 5). The annual mean temperature increased from 15.8ºC in 1988 to 16.8ºC in 2002. Background studies have shown that this increase was not due to the urbanization of the area.

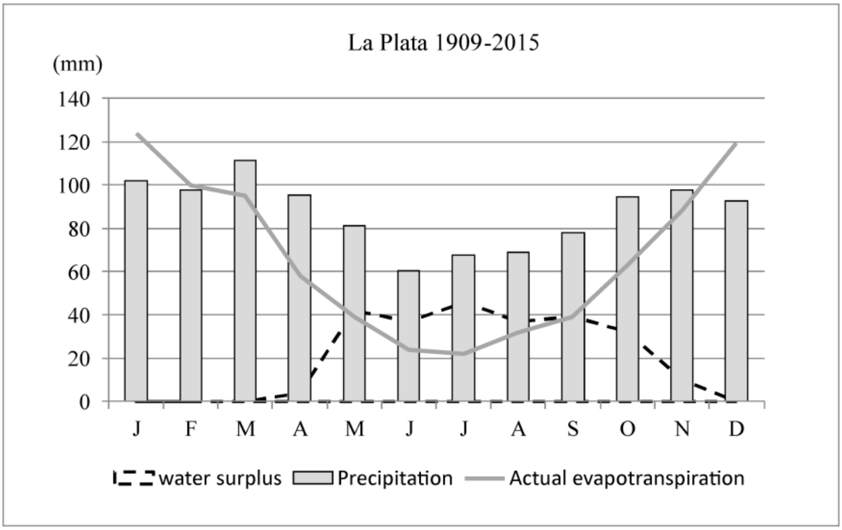

Figure 6. Water balance of La Plata (1909 – 2015).

The mean annual precipitation from 1909 to 2015 was 1048 mm/y. The actual evapotranspiration, obtained from the water balance (Thornthwaite and Matter, 1955), is 783 mm/y. Fluvial drainage and infiltration reach 53 mm/y and 225 mm/y, respectively (Figure 6).

The natural hydrologic behavior was analyzed through the evaluation of the water balance in a neighboring river basin (Arroyo El Pescado) with similar hydrologic characteristics, but without the effect of human impact. The Arroyo El Pescado is effluent with respect to groundwater, and without intensive groundwater exploitation. The runoff for significant rainfall events (above 120 mm and five-day duration) varies between 1% and 60% of precipitation (Kruse et al. 2004). The analysis of the water table variations (1989-2000) shows clearly changes connected with meteorological oscillations. Recharge estimations in daily periods give values between 20% and 65% of rainfall above 150 mm and five-day duration, associated with important water excesses for dry prior conditions of the soil (Laurencena et al. 2002).

The phreatic water chemical composition of Arroyo El Pescado is sodium bicarbonates with salinities between 370 and 1600 mg/L, evolving to sodium chloride with 8,000 mg/L in the regional discharge zone (coastal plain). The surface water presents the same composition, with smaller salinity values varying between 400 mg/L in the upper creek basin to 950 mg/L in the coastal plain. The progressive increasing salinity, particularly of chloride contents, is noticeable downstream, which is an evidence of groundwater discharge into the stream (Gonzalez and Laurencena, 1988).

The Arroyo del Gato basin presents changes in natural water balance and the interrelation of surface water and groundwater. The existence of impervious zones (urban areas) diminishes the water availability to compensate the actual evapotranspiration, thereby causing an important increase in the excesses of the water balance, with the subsequent increase in volume and speed of runoff. It must be pointed out that the present stream regime is characterized by important floods of short duration (1 or 2 days), favored by drainage from the urban zone. The runoff in the urbanized area for storm events lasting 5 days and greater than 120 mm, oscillates between 23% and 90% of the precipitation. The smaller values correspond to dry conditions of preceding humidity, whereas the larger ones correspond to humid conditions. These magnitudes of runoff in the hydrologic balance allow deducing a decrease of excesses capable of infiltrating (Kruse et al. 2004).

Chemically, groundwater of the Arroyo del Gato basin is of similar major ionic characteristic to the Arroyo El Pescado. On the other hand, there is a marked increase in nitrate content reaching values higher than those recommended for human consumption; in many cases, more than 100 mg/L, forcing the abandonment of exploitation wells (Kruse et al. 2003). Surface water presents a high coloring and content of suspended substances, product of spills of human activities in the area (industrial effluents, sewer, etc.). The degree of contamination is verified by the high concentration of phosphorus (>0.25 mg/L of phosphates), organic substances and some pesticides. Since in this case there is a flow from the stream towards groundwater, the polluting agents can migrate towards the phreatic aquifer.

GROUNDWATER EXPLOITATION

In the urban area the Puelche aquifer is overexploited, which has generated depression cones exceeding 70 km^2. Due to hydraulic interconnection between aquifers, this deepening of levels affects the water table.

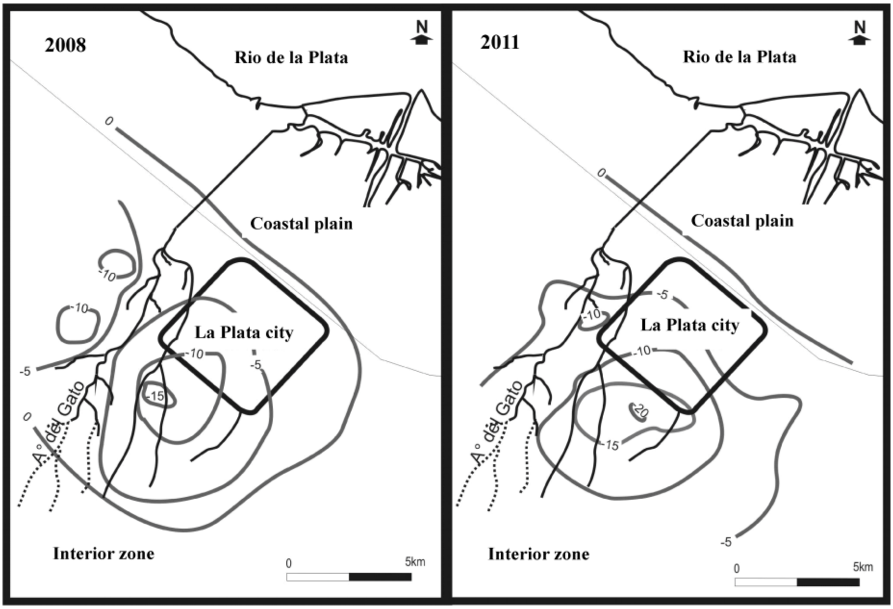

Figure 7. Piezometric map of La Plata. 2008 and 2011.

At present, the development of relatively stable depression cones has produced a change in the natural hydraulic gradients of the water table, thereby modifying the natural interrelation between surface water and groundwater. This alteration becomes evident in the upper and mid creek basin where there is a clear influence of the watercourse on the water table (Figure 7). The average groundwater volume withdrawn for human consumption is 73 hm^3/y. The direct contribution of the aquifer is approximately 70% (51 hm^3/y) of the total exploited volume. The remaining 30% is supplied by infiltration of water seepage from gutters, water mains, sewer systems and urban irrigation. This means values on the order of 22 hm^3/y (314 mm/y) (Facultad de Ingeniería, 1994).

DISCUSSION AND CONCLUSION

The above factors show the complexity of the environmental hydrogeology problems and the fragility of the system to external agents. Remediation actions are to be carried out against past abuses that were both a direct consequence of the lack of a clear management policy on the use of natural resources, and the wrong belief that water resources were inexhaustible. To mitigate further economic losses and environmental damages, water management policies must be adopted. Policies have to be directed to conserving the resources, protecting the groundwater reserve and avoiding all possible source of contamination. The application of plans to reach a balance between the water demand and environmental protection is essential, and represents a fundamental base for a sustainable exploitation that will preserve freshwater reserves for future generations. Recommended actions include the exploitation of freshwater resources of rural areas, preventing their urbanization and development from potentially polluting activities.

At present, there is an overexploitation of the Puelche aquifer that has modified the natural hydraulic conditions, collaterally affecting the hydrochemical characteristics because of contamination from human wastes. A lack of sewer systems in some areas, as well as spills from water distribution networks favour accumulation and/or enrichment of polluting agents. Since a significant increase in the demand for water, particularly drinking water, is predicted in future years, it is essential to intensify groundwater assessment to get insight in water reserves, to protect recharge areas and delimit discharge zones. The suggested actions include:

1. Concentrate most groundwater exploitation in rural areas such as the Arroyo El Pescado creek basin), limiting their urbanization and the development of potential polluting productive activities.
2. Groundwater exploitation should be aimed to satisfy drinking water demand.
3. Impose the use of surface water from the Rio de la Plata for all the water needs not requiring drinking properties.
4. Optimize groundwater volumes allocated for potable, industrial and irrigation uses and balance them with groundwater discharge and natural recharge.

Based on the vulnerability and risk of the resource, it is necessary to expand the sewer network in the urban zone, as well as to limit the use of herbicides, pesticides and fertilizers in the countryside. In addition, it is necessary to establish a monitoring network to control groundwater and its withdrawn volumes.

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Chapter 3

THE EVOLUTION AND CHARACTERISTICS OF NATURAL WATERS UNDER AN ARID CLIMATE IN NORTHERN XINJIANG (CENTRAL ASIA)

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ABSTRACT

This paper analyzed the physico-chemical characteristics of natural waters in a drainage system of northern Xinjiang (Central Asia) for an

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identification of the geological evolution and recharge mechanism of natural waters in an arid environment. The studied waters are different in mineralization but are typically carbonate rivers and alkaline in nature. No Cl-dominated water type occurs, indicating an early stage of water evolution. Regolith and geomorphological parameters controlling ground-surface temperature may play a large role in the water geological evolution. Three main morphological and hydrological units are reflected in water physico-chemistry. Climate influences the salinization of natural waters substantially. Direct recharge from seasonal snow and ice-melt water and infiltration of rain into the ground are significant recharge processes for natural waters, but recharge from potential deep groundwater may be less important. The enrichment of ions in lakes has been mainly caused by evaporation rather than through the quality of the recharged water.

Keywords: hydrogeochemistry, arid environment, recharge mechanism, climatic effect, Central Asia

1. INTRODUCTION

Water in the Earth system is not only one of the key components but also a major agent of the biogeochemical cycles that link the lithosphere, biosphere and atmosphere. In the central Asia, high mountains, particularly the Tibetan Plateau and Tianshan Ranges, function as barriers for atmospheric circulation and keep moisture from reaching an extensive region in western China, causing arid and hyperarid climatic conditions (Domros and Peng 1988; Sun et al. 2010). Fresh water in these regions is definitely a non-substitutable resource upon which humans and ecosystems depend. The arid land of northwestern China is significant repositories of information relating to hydrological evolution and climatic changes in central and eastern Asia. Northern Xinjiang in northwestern China, the geographical centre of the Asian Continent, is an extremely arid and ecologically weak region. An understanding of the source of natural waters in the northern Xinjiang watersheds is significant not only to policy makers for regional planning, but also to scientists interested in the hydrological cycles in an arid environment, and the climate change in Northern China and other arid regions of Asia.

Most of the rivers in the northern Xinjiang drainage system originate from peripheral mountain glaciers and snow and drain areas of diverse geology and climatic conditions, with lower reaches in the desert environment. Geochemical studies of these waters are of considerable importance for a better understanding of the sources of the natural water resources and the influencing factors. At present, the Xinjiang province has become the focus of attention in China due to its rapidly increasing population and an evident climatic variation. Both of these factors consequently increase stress on regional water resources and environmental protection. Understanding the evolution and recharge mechanisms of natural water is a fundamental issue for both aquatic ecologists and water resource managers (Meyer et al. 1988; Kimbadi et al. 1999). Until now, except for a few studies about the chemical weathering and weathering flux in these regions (Zhu et al. 2011, 2012, 2013a, 2013b, 2015, 2016a, 2016b), little works were carried out in the northern Xinjiang drainage systems. Using the area of northern Xinjiang as an example, this paper provides insight into the physicochemistry of natural waters in arid environment. The geochemical evolution and recharge mechanisms of natural water and the climate effect in this region are emphatically discussed.

2. REGIONAL SETTING

The geographical location of the northern Xinjiang (China) ranges between 78° and 90°E and 42° and 50°N. It is approximately 603,000 km^2 in area and is bounded by the Tianshan Mountains to the south and the Altai Mountains to the north. Elevations increase from <500 m above sea level (asl) in the centre of the Zhungarer Basin to >3000 m asl in the south and north ranges (Figure 1c). The topography is generally flat in the centre plain and is rather cragged in the peripheral mountainous areas. The wide piedmonts and pediment plains are marked by the Gobi desert, grassland for herding and oasis areas with intensive agricultural activities. The land is controlled by an arid temperate continental climate. The mean annual air temperature is about 5°C, with a minimum of -10°C to -20°C in January and a maximum of 28°C to 33°C in August. The regional precipitation is derived mainly from westerlies, with a mean annual precipitation rate of 60-150 mm in the centre plain and 200-500 mm in the surrounding mountainous areas (Figure 1b). While the potential evapotranspiration is approximately 1000-3500 mm per year, it varies in aridity both seasonally and along the elevation gradient across northern Xinjiang, due to the distribution patterns of seasonal precipitation, temperature and relative humidity and the orientation of delivery of moisture by the westerlies.

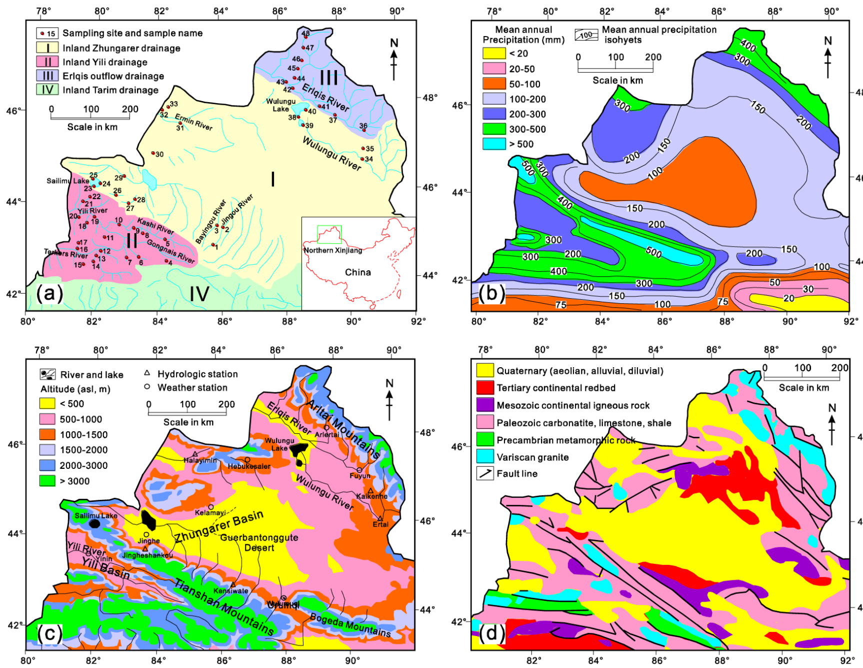

Figure 1. (a) Hydrological setting and sampling locations map, (b) mean annual precipitation isohyets distribution map, (c) topographical map and (d) lithological-distribution map of the northern Xinjiang (Central Asian) in China.

The northern Xinjiang drainage system includes three watersheds: the Zhungarer, the Yili and the Erlqis (Ma 2002) (Figure 1a). The Zhungarer and Yili watersheds are inland continental watersheds and the Erlqis watershed drains into the Arctic Ocean. Water resources in northern Xinjiang are mainly distributed in Yili (170.9 × 10^8 m^3), Arltai (129 × 10^8 m^3) and Tacheng districts (61.6 × 10^8 m^3) and the total volume of the surface water in northern Xinjiang is about 435.7 × 10^8 m^3. The temporal distribution of runoff in a year is extremely heterogeneous with 50-70% in summer, 10-20% both in spring and autumn, and less than 10% in winter. The uneven spatial-temporal distribution of water resources and dry climate environment determine the complete dependence of oasis agricultural activities on water. The Zhungarer Basin (379,000 km^2) is located at the central part of northern Xinjiang and is the geographic centre of the Asian Continent. The basin is a structural depression filled with unconsolidated Quaternary and Tertiary sediments as much as 500-1000 m in thickness (XETCAS et al. 1978), and is an extension of the Palaeozoic Kazakhstan block surrounded by Palaeozoic folded mountains. Aeolian deposits are widespread in this basin. The Gulbantonggute Sand Sea (48,800 km^2) is located in the central part of the basin. A large geographic distance from the surrounding oceans and the presence of the rain-shadow effect due to the surrounding orographic conditions is responsible for the arid climate of the Zhungarer Basin, which is necessary for the creation of the sand desert. Most rivers in the Yili watershed converged into the Yili River at their lower reaches. The Yili River is a large international river running from its sources in the northeast Borohoro Mountains and southeast Halik Mountains, both branches of the eastern Tianshan Mountains, and flowing eastward through the Yili basin into Kazakstan (Figure 1). It drains igneous and metamorphic Precambrian (An€) and Variscan (γ_4) granite, Carboniferous (C_1, C_{2+3}) carbonatite and limestone and Quaternary sediments (Ma 2002) (Figure 1d). The Yili River is about 430 km long inside the Yili watershed and contains three major tributaries in the catchment: the Kashi River in the northeast, the Gongnais River in the east and the Terkers River in the south and southeast. Much of the drainage areas of the tributaries are dominated by the sedimentary, mostly carbonate, lithologies (Figure 1d). The Erlqis watershed has headwaters in the southern slopes of the Arltai Mountains (Figure 1a). Rivers converge into the Erlqis River at their lower reaches, and the Erlqis River is also a large international river, flowing through Kazakstan northward through Russia and finally into the Arctic Ocean. The stem channel of the Erlqis River is about 500 km long inside the Erlqis watershed. The Buerjin River is one of the most important tributaries of the Erlqis River and is about 250 km long and originates in the glaciers of the Youyi Mountains (4373 m asl). The lithologic outcrops in the catchment are mainly the Devonian marine carbonate, clastite (D2, D2 + 3), and the igneous Variscan (γ_4) granite and Quaternary sediments (Ma 2002) (Figure 1d).

3. METHODS

Field investigations were carried out on the whole region of northern Xinjiang during summer-autumn season in 2008. Chinese 1:50,000 scale topographic maps, a prismatic compass, a Thrommen altimeter and a Garmin GPS were used for orientation. All locations and elevations were recorded using GPS and topographic maps. Water samples were collected under natural flow conditions in one-liter polyethylene bottles from various parts of the Yili, Zhungarer, and Erlqis watersheds (Figure 1a), including river stems, stream channels, hill slopes, wells, lakes, ponds, man-made trenches and reservoirs. Taking into account that the tributaries reflect a much broader variety of geological, biological, and population patterns than do main stem rivers (Pawellek et al. 2002), it was of interest to sample tributary water to look for common features reflected in their hydrochemistry. Some pristine streams draining forested catchments were chosen in the Tianshan and the Arltai Mountains. All waters were surface-sampled except for well water extracted from pump shafts. Most water samples were colorless, but a few were yellow, gray or turbid in colour due to dissolved iron content or suspended solid particles. The colored river water samples primarily drained through the south and north piedmont areas of the Tianshan Mountains, with deep coves of loess and loess-like soil. Because no river and spring exist in the hinterland of the Gulbantonggute Desert, no surface water samples was collected for comparison from others in this work.

Water samples were filtered through a 0.45 μm Millipore membrane filters in the field and analyzed in the institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Analysis of water samples included total dissolved solids (TDS), pH, and ion concentrations. Ions were mainly measured with a DX600 Dionex ion-chromatography. Temperature (T), pH, and TDS were measured in situ using a portable Multi-Parameter Analyzer (Eijkelkamp 18.28). The water samples for cation analysis were acidified with hyper-pure HNO_3 below pH 4.5. Cations and anions were determined by ion chromatography (IC, Dionex 600) with deionized water (EC < 2.1 μS/cm) as the dilute base. The eluents used were 20 mmol/L MSA (methanesulfonic acid) at pH 4.5 and conductivity of approximately 400 μS/cm for cation analysis and 3.5 mmol/L Na_2CO_3, 1.0 mmol/L $NaHCO_3$ at pH 8.5 for anion analysis, respectively. One replicate for each sample was taken for ion analysis, and the instrument was recalibrated after every 5 samples. The alkalinity was measured with a Hach digital titrator using the Gran method (Wetzel and Likens 2000) within three days after sampling.

4. RESULTS

Major physio-chemical and chemical properties of the water samples studied are statically listed in Table 1. The data show that the natural water at various sites is different in terms of mineralization, with TDS ranging from 24.6 to 6200 mg/L, the mean being 580 mg/L. More than half of the investigated samples belong to fresh water (TDS < 1000 mg/L), and the remainder to brackish water (TDS 1-10 g/L). All natural water is alkaline, and pH values range from 7.0 to 9.81, with an average value of 7.87. In the Piper's diagram the natural waters are distributed in fields where alkaline earths exceed alkalis and strong acids and weak acids dominate partially in composition (Figure 2). There are four main water types: Ca-HCO_3, Ca-NDA (non-dominant anion), Ca-SO_4 and NDC-NDA (non-dominant cation) or Na-NDA. Ca-type water is most widely distributed in the study area. The Ca-HCO_3 and Ca-NDA types mainly occur in the montane areas and the low-pitched piedmont zones. The Ca-SO_4 and Na-SO_4 types are mostly distributed in the transition band between oasis and desert plain. Mg-type water merely occurs in the Sailimu Lake. There is no Cl-dominated water type that occurs in the study area (Figure 2).

Table 1. Statistical summary of the physical parameters and major ion concentrations determined in the study water samples (TH, total hardness; SAR, sodium adsorption ratio)

Parameter	Maximum	Minimum	Average	Median	10^{th}	90^{th}	SD
pH	9.81	7.00	-	7.85	7.33	8.24	0.47
Eh	-21.0	-187	-72.6	-72.5	-94.6	-41.8	27.6
EC (μs/cm)	5380	46.3	864	352	162	3426	1258
TDS (mg/L)	6200	24.6	580	186	86.1	1843	1071
Li^+ (mg/L)	0.13	nd	0.02	0.01	nd	0.04	0.02
Na^+ (mg/L)	1673	1.66	105	6.86	2.60	272	281
NH_4^+ (mg/L)	0.17	nd	0.02	nd	nd	0.03	0.04
K^+ (mg/L)	77.7	0.49	8.48	1.63	0.82	25.9	17.4
Mg^{2+} (mg/L)	190	0.63	27.2	6.49	2.44	81.8	49.5
Ca^{2+} (mg/L)	91.9	3.05	29.1	26.4	14.0	48.0	16.7
F^- (mg/L)	3.04	0.02	0.31	0.18	0.06	0.54	0.51
Cl^- (mg/L)	648	1.83	74.5	6.91	2.97	223	160
NO_3^- (mg/L)	36.5	nd	4.96	2.88	0.72	8.89	6.62
SO_4^{2-} (mg/L)	2655	2.52	205	45.3	9.01	682	437
HCO_3^- (mg/L)	799	9.76	117	69.4	29.7	283	142
TH (mg/L)	824	10.2	184	102	47.9	436	209
SAR	28.2	0.058	1.97	0.278	0.094	4.56	4.85

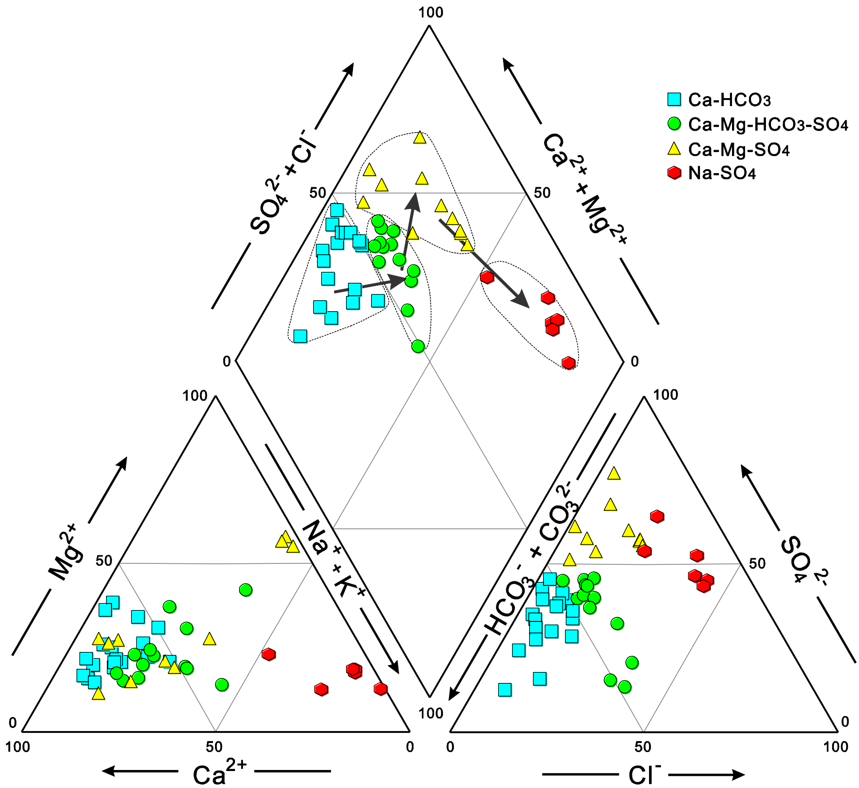

Figure 2. Piper plot of the study water samples.

5. Discussion

5.1. Geochemical Evolution and Distribution

The natural waters in northern Xinjiang are similar to the majority of the large rivers on earth, which are typically carbonate rivers and alkaline in nature (Meybeck 1987). Compared with the upper ranges of typical values for major world rivers and the lower ranges for major pristine rivers (most common natural concentrations - MCNC) (Figure 3), such as the Amazon and Mackenzie (Meybeck and Helmer 1989; Meybeck 1996), the mean major-ion concentrations of the study waters are almost in excess of typical natural values of the major world rivers (Figure 3), except for Ca^{2+} and HCO_3^-. This suggests that the natural waters in northern Xinjiang fall close to the upper limit of concentrations in major world rivers, classified as "salted" by Meybeck (1996). Furthermore, the study waters are notably characterized by an enormous range over three orders of magnitude for concentrations and yields than that of global rivers (Figure 3). This indicates a definable spatial variation of water chemistry and quality in the study watersheds.

Cl-type water is usually one of the major water types in the desert environment in northern China, such as in the Taklamakan Desert (Zhang et al. 1995; Zhu and Yang 2007) and the Badain Jaran Desert (Yang and Williams 2003; Zhu and Yang 2010; Zhu et al. 2012). Cl-dominated water type does not exist in the study area (Figure 2), indicating that the natural waters in northern Xinjiang are still at the early stage of water evolution.

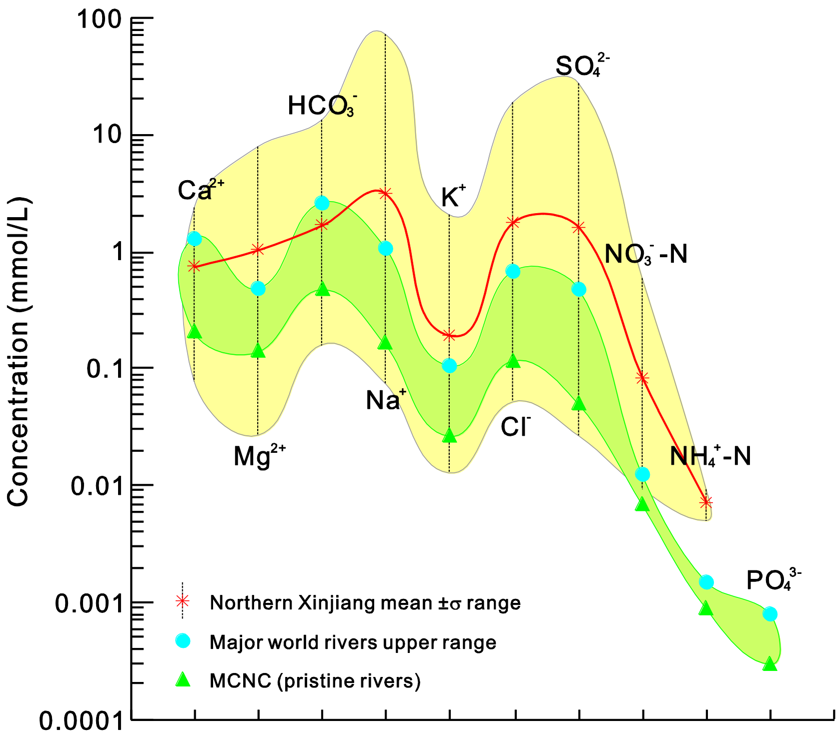

Figure 3. Typical ranges for major ions in the natural waters in northern Xinjiang. Also marked are the upper limits for these components in major world rivers and the median concentrations in pristine rivers (MCNC) (Meybeck and Helmer 1989; Meybeck 1996).

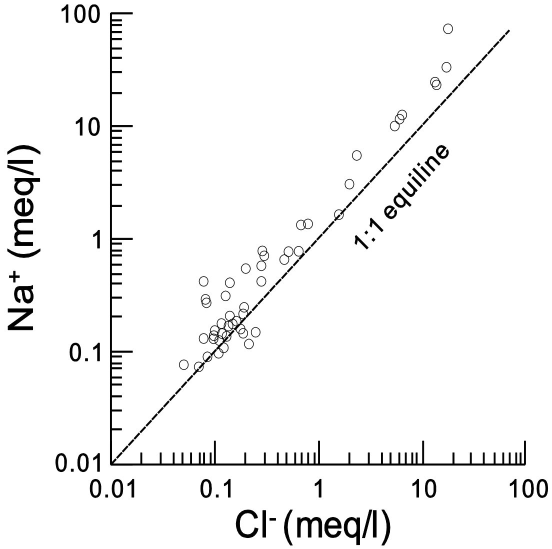

Figure 4. Scatter diagram of the concentrations of Na^+ vs. Cl^- of the study waters.

The large variation in Ca^{2+} and Na^+ concentrations in the natural water samples from the study area (Table 1 and Figure 2) may theoretically reflect local mineralogical changes in the sediments and in the carbon dioxide produced by biological processes in their surface layers. However, biogenic weathering might not be a key factor, because the natural water here is alkaline in general. The CO_2 reactions in the natural water are possibly not very active at many sites because of alkaline conditions and limited vegetation on the surface. The heterogeneity of the ionic compositions (Figure 2) may also be caused by local variations in the mineralogy of the natural water reservoir and geochemical processes occurring in the aquifer. Principally, the amount of sodium rises as the chloride content increases in the investigated samples (Figure 4), supporting the view that geochemical processes play a role in the chemistry of natural water. Referring to the Na/Cl ratios, part of samples (mostly from mountainous areas) with lower TDS lie very close to the 1:1 ratio line (Figure 4), indicating that sulphate and other salts are relatively abundant in the natural water with higher TDS (mainly under fluvial-plains and desert environments). The regolith and geomorphological parameters controlling ground-surface temperature may play a large role in rock weathering regime and so in the water chemistry, because solution of lithological components is controlled to a large extent by the ground temperature in a periglacial landscape and its surrounding areas (Beylich et al.

2004). Such as in areas of shade, cold ground and thin regolith, the TDS of natural water (surface water and shallow groundwater) is low, whereas the TDS is high in areas exposed to intensive radiation. Data from the artic-oceanic drainage basin of northern Sweden (Latnjavagge) show that water chemistry may vary considerably in a small area with very homogeneous lithology but great slope segments. The regolith in northern Xinjiang area varies in thickness from less than a meter to more than 5 m between upper and lower slope segments.

The water samples from the oasis areas in the Zhungarer basin where the community administrations are located show much higher TDS than samples from more pristine areas. This is probably caused by two processes: (1) direct pollution reflecting increased population and agricultural density and (2) re-seepage of wastewater. It appears that the wastewater can infiltrate into the natural water systems quickly, because the irrigation and housing, and therefore waste and dung depot, are very close and easy to the aquifer due to the close hydrological conditions with low topography in the basin. Compared with the nitrate contents (0.5-7.7 mg/L) in the surface waters, groundwater samples in the Zhungarer watershed have clearly higher concentrations of nitrate (22-37 mg/L). The high concentration of nitrate in these samples is probably related to the decomposition process of untreated waste. In fact, the nitrate concentration is quite high in the majority of the ground water samples from the entire study area. In the arid and desert environment, both humans and their animals depend on the groundwater (wells) to live. Therefore human influence is quite strong around the wells and the dung depot is often located not far from the wells. This may be the reason for the high concentration of nitrate in the water samples. There is no wastewater treatment system in this region yet. In the interests of the health of local residents it is necessary to add sewage treatment.

5.2. Recharge Mechanisms of the Natural Waters

The possible mechanisms for natural water (especially river and shallow groundwater) recharge in the areas of the northern Xinjiang are: (a) direct infiltration of rain into the ground; (b) direct recharge from seasonal snow and ice-melt water; (3) recharge from potential deep groundwater. The first two processes are thought to be significant, but the third may be much less important, because the northern Xinjiang watersheds form a various ranges in a desert landscape. Based on the tectonic structure of mountain-basin couples, it is concluded that the recharge of the shallow groundwater is mainly through infiltration of seasonal snow and ice-melt water derived from mountain areas and local precipitation that infiltrates downwards quite quickly owing to the loose nature of the regolith. Due to the large temporal and spatial variability of rainfall, infiltration is related to the amount of precipitation of each event. From dried channels in the fields one can assume that there may be ephemeral streams and ponds in the study area when it rains. As a result, the overall recharge process is quite heterogeneous. The clear difference in ion concentrations suggests that the hydraulic relationship between various sampling sites is weak.

For the areas of fluvial plain in the Zhungarer, we consider that the precipitation directly onto the rivers, lakes and reservoirs plays a minor role in the recharge today, because the amount of precipitation is much smaller than the evaporation occurring on the water surface. Field observations indicate that all rivers in these areas were recharged mainly by mountain stream water and partially by groundwater at present time. Owing to the isolated geomorphological basin structures, it is unlikely that the recharge mechanisms might have fundamentally changed in the past. The large range in chemical composition of water samples suggests not only the heterogeneity of the recharge conditions in the study areas, but also a possible mixing with enriched waters that could be in different aquifers. However, the input from other regions (via surface runoff or groundwater inflow) seems to be rather insignificant in the local water cycle. Besides, a large proportion of rain is maybe added to the shallow groundwater system because of rapid infiltration in the loose and sandy sediments. Observations and interviews with local residents suggest that the water from the shallow aquifer can meet the water demand of inhabitants with traditional life styles and adequate livestock grazing in the desert environment of northern Xinjiang.

The highest TDS concentrations were observed at some lake depressions (such as the Salimu Lake) around the central Zhungarer watershed. From field observation, it is assumed that the Salimu Lakes are mainly recharged by glacier/snow waters, because it is located in a highland depression surrounded by high mountains and there is surficial inflow but no outflow. The major ions in the lake are Mg^{2+} for cations and SO_4^{2-} for anions. At present, Salimu is one of the largest lakes in northern Xinjiang and has relatively high TDS (1850 mg/L). Compared with the chemistry of other lake samples, the proportions of sodium and chloride are much lower in the Salimu lake water. From a global point of view, the dominant ions in most saline lakes are Na^+ and Cl^-, and occasionally in some less saline lakes, Na^+ and HCO_3^-/CO_3^{2-} (e.g., Day 1993).

It is reasonable to believe that the brines of these lakes were formed by long and intensive evaporation, because Na^+ and Cl^- are often associated with evaporites. We can exclude the halite origin for the Salimu Lake. However, Mg^{2+} and SO_4^{2-} are also often associated with evaporites. Dissolution of sulphates (such as gypsum and anhydrite) may be an important source here. In general, major ions in saline waters were derived from the catchment or the substratum (e.g., Kilham 1990). However, atmospheric precipitation should not be ignored as a potentially significant source of ions (Eriksson 1985) in the water of the study area because of frequent dews and rimes. In many large saline lakes of northern China and Mongolia, Cl^-, SO_4^{2-} and HCO_3^- are almost equally predominant anions, while Na^+ and K^+ are strongly dominant cations. The salts of these lakes were thought to have originated from high evaporation and soil salinization (Egorov 1993). The salinity of the Chinese lakes increases westwards, consistent with the trend of increasing aridity. Both natural climatic changes and irrigation activities have caused decadal variations in the salinity in these lakes. From limnological analysis of different world regions, it was concluded that large, deep, saline lakes often contain alkaline, sodium rich waters with considerable chloride, sulphate, and carbonate plus bicarbonate (Melack 1983). The chemistry of lakes in the northern Xinjiang drainage basins is, to a considerable extent, consistent with those of large lakes. Also, from this point of view, it appears that the enrichment of the ions in the lakes has been mainly caused by evaporation, rather than through the quality of the recharged water.

5.3. Response to Climate

The regional distribution pattern of chemical water types (Figure 2) reveals that a transitional trend exists between natural waters in the northern Xinjiang drainage basins. Water types are generally transformed from Ca-HCO_3 to Ca-Mg-HCO_3 to Ca-Mg-SO_4 and to Na-SO_4. This trend is spatially accompanied by the altitude variation of landscapes in the order of mountains, pediments, piedmont plains and desert plains. It indicates a potential control of a vertical zonality of temperature and relevant geological effects on the natural water evolution. Besides this trend, another kind of zonal distribution of hydrogeochemistry also exists in the northern Xinjiang drainage basins. For example, the relatively wet zones, with AMP > 200 mm in three watersheds, consist of the Ca-HCO_3, Ca-NDA and NDC-NDA types. In the relatively dry zones, with AMP < 200 mm, however, the Ca-SO_4 and Na-SO_4 types predominate. The Ca-HCO_3-dominated chemistry of river water in the relatively wet zones couples well with regional carbonate lithological distributions (Figures 1d). It confirms that rock weathering and the regional lithologic distributions have a major effect on the evolution of river chemistry in the wet zones. The precipitation processes can accelerate the rock weathering processes (White and Blum 1995). The water types in dry zones tend to be relatively uniform. Because the lithological distributions are not homogeneous, evaporation processes, which can result in the selective precipitation of solute fraction ($CaCO_3$) and subsequent changes in water chemistry as water moves downstream in the relatively arid zones (Gibbs 1970; Kilham 1990; Feller 2005), could be responsible for the accumulation and evolution of sodium and sulphate salts. It indicates a major effect of climate rather than geology on the evolution of water chemistry in dry zones.

The strong relationship between the annual mean summer precipitations (AMP) in northern Xinjiang and the altitudes of the sampling sites in this study can be well expressed as AMP = 0.14 × altitude + 101.3 ($r = 0.88$, $p < 0.005$). The total dissolved solids in most samples decreased in concentration with the increasing altitude (Figure 5). It indicates a potential influence of precipitation on dissolved materials in the water. The fact that rock types are not distributed according to the altitude (Figure 1c, d) implies that topography and temperature, in addition to rock type and weathering, affects water chemistry indirectly by influencing AMP/evaporation processes.

In the central parts of the study watersheds, evaporation probably influences the salinization of surface and ground water substantially, because the TDS value of river water clearly varies along their channel courses, such as the Erlqis, Wulungu, Jingou, Gongnais and Yili rivers (Figure 5). The river waters in the middle reaches of the Jingou, Gongnais and Wulungu have TDS values of 90, 95 and 321 mg/L, respectively, and gradually change to higher values of 112, 147 and 2000 mg/L after flowing about 70, 100 and 300 km downward, respectively. The Jingou, Gongnais and Wulungu rivers have few tributaries over their water courses (Figure 1a), so the waters flowing along the lengths of these courses do not mix extensively with water from different tributary sources. In addition, the seasonal changes of discharge and sources cannot be the reasons for the variation in the dissolved solid concentrations for one-day-collected samples from a single river. Accordingly, the increase of TDS from upper reaches toward lower reaches in these rivers can be interpreted in terms of evaporation and dissolution of soil salts along their river courses. Due to the relatively fixed channel course at present, the dissolution of soil salts alone river bed maybe does not vary greatly. So if evaporation processes cause the change of concentration of dissolved material during water flow, given no change in the flow speed of ~5 km/h, it is intense enough in these drainage basins that runoff can decrease by one-third to one-fifth during one day.

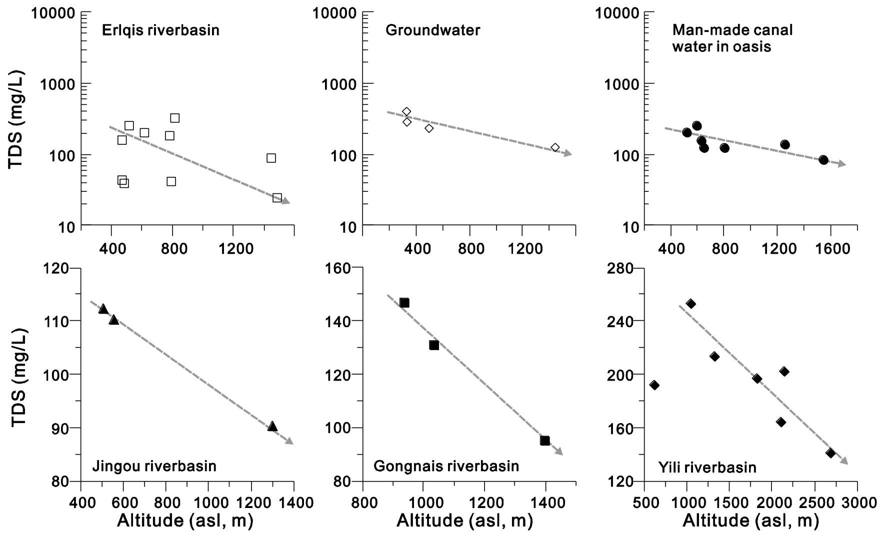

Figure 5. TDS vs. altitude (m, asl) of the study water samples.

CONCLUSION

The physico-chemical characteristics of the natural waters in northern Xinjiang drainage system, as well as the climatic, geological and topographical context where they flow and reside, allowed the identification of fluvial geological evolution and recharge mechanism of the natural water resources in arid environment. The natural water at various sites in the study area is different in terms of mineralization and is similar to the majority of the large rivers on Earth in general, which are typically carbonate rivers and alkaline in nature. However, there is no Cl-dominated water type that occurs in the study area, indicating that the natural waters in northern Xinjiang are still at the early stage of water evolution. The regolith and geomorphological parameters controlling ground-surface temperature may play a large role in water chemistry and its evolution. Evaporation influences the salinization of natural water substantially. The high concentration of nitrate in oasis water is probably related to the decomposition process of untreated waste. Direct recharge from seasonal snow and ice-melt water and infiltration of rain into the ground are thought to be significant recharge processes for natural water in the study area, but recharge from potential deep groundwater may be much less important. The chemistry of lakes is to a considerable extent consistent with those of large lakes in the world but the enrichment of the ions in the lakes has been mainly caused by evaporation, rather than through the quality of the recharged water. Two kinds of zonal distribution of water types exist in the northern Xinjiang drainage basins. It confirms that temperature-and-precipitation-dependent geological weathering and lithologic distributions have a major effect on the evolution of water evolution in the wet zones and a major effect of climate (evaporation) rather than geology on the water evolution in dry zones.

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Chapter 4

IMPACTS OF DEVELOPMENT ON RIVER FLOWS

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ABSTRACT

Flows of rivers throughout the world have been altered by population and economic growth and accompanying water resources development. River flow characteristics are changed by construction of dams and other facilities to control floods, generate hydroelectric energy, and provide reliable water supplies, diversions for agricultural, municipal, and industrial needs, and return flows from surface and groundwater supplies. Impacts on hydrology and water availability associated with climate change due to global warming are also of major concern in hydrologic science and water management. Alterations in flow characteristics differ greatly across the spectrum from low flows to median flows to infrequent extreme flood flows. Gradual permanent increases or decreases in stream flow may be difficult to detect due to the great continuous natural variability that hides long-term trends. This chapter reviews studies of flow alterations found in the literature and then employs a modeling system and databases for the river systems of Texas to investigate characteristics of river flows and long-term impacts thereto resulting from

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development and other causative factors. Researchers have applied statistical trend analysis methods, watershed precipitation-runoff models, and river-reservoir system management models to quantify flow alterations for river systems throughout the world. Flow alterations in Texas are illustrative of river systems in many other regions of the world. A water availability modeling system developed to manage water resources in Texas provides a unique opportunity to explore alterations to river flows for a broad diverse range of climate and hydrologic conditions, population and economic growth, and water resources development and management practices. Trends of long-term changes in precipitation during 1940-2015 are not evident in Texas. Flows for reaches of major rivers have been impacted significantly, in some cases dramatically, by water development. The flow increases and decreases vary greatly with location.

Keywords: rivers, reservoirs, flow alterations, trend and frequency analyses, simulation

INTRODUCTION

Flows in rivers are naturally highly variable with continuous, storm-event, seasonal, and multiple-year fluctuations reflecting the extremes of floods and droughts as well as more frequent but less severe variations. Long-term changes in flow characteristics result from long-term changes in climate, watershed land use, and water use, and construction of river regulation structures and water resources development projects. Detecting long-term alterations in river flows is difficult due to the great continuous natural flow variability.

River flows throughout the world have been impacted by various combinations of population growth, urbanization, agricultural and industrial development, construction of river regulation structures and water storage and conveyance facilities, water use diversions and return flows, and interbasin transport of water resources. The impacts of human activities on low flows are typically very different than on high flows. For example, regulation of rivers by dams reduces flood flows but may increase low flows at downstream locations.

Climate change associated with global warming may cause increases or decreases in mean precipitation and mean evapotranspiration and changes in the variability of these and other climatic variables that in turn affect stream flow. Watershed land use changes affect runoff quantities. Water supply diversions decrease streamflow. Wastewater treatment plant effluent and irrigation return flow from water supplied from groundwater sources or reservoir storage may contribute to maintaining base stream flows during dry periods. Evaporation from reservoir water surfaces represents a major impact of reservoir project construction. Reservoirs are operated to reduce flow variability, including both increasing low flows and decreasing high flows along with providing water supply reliability and flood risk mitigation.

An enhanced understanding of long-term changes in river flow characteristics contributes to environmental protection/restoration programs and various other water resources management activities. Alterations in the natural flow regime of rivers have important consequences from the perspectives of instream flow needs for fish and wildlife, freshwater inflows to bays and estuaries, impacts on other environmental resources, aesthetics, recreation, water supply, and various other aspects of water resources development, management, and use. Decreasing flows affect the assimilative capacity of rivers to absorb pollutants, affecting waste-water treatment and non-point source pollution prevention endeavors. Municipal, industrial, and agricultural water supply and multiple-purpose reservoir system operations are significantly impacted by changes in available stream flow.

Computer modeling systems for assessing water availability and supply reliability are important for effective water resources development, allocation, and management. Modeling systems require homogeneous long-term sequences of historical daily, weekly, or monthly stream flow data that represent either natural conditions without human impact or some other specified condition of river basin development. Past observed flows are adjusted in modeling systems to represent specified conditions of development and water regulation and use. Dealing with nonstationarity is an important aspect of water availability modeling.

This chapter explores (1) the characteristics of stream flow alterations under various situations and (2) modeling and analysis techniques and metrics for quantifying flow changes. The chapter begins with a review of the published literature and then focuses on studies of the river systems of Texas conducted by the author and his research team at Texas A&M University (TAMU) over the past twenty years.

Texas is a large state characterized by extreme hydrologic variability both spatially and temporally, rapid population growth, declining groundwater supplies, and intensifying demands on surface water resources (Wurbs 2015a). Texas is representative of both the drier western and wetter eastern regions of the United States (U. S.). Climate, geography, economic development, water use, and water management practices vary dramatically across the 15 major river basins and eight coastal basins of the state from the arid western desert to humid eastern forests, from sparsely populated rural regions to the metropolitan areas of El Paso on the Rio Grande, San Antonio on the San Antonio River, Austin on the Colorado River, Houston in the San Jacinto River Basin, and Dallas and Fort Worth in the Trinity River Basin. A statewide Water Availability Modeling (WAM) System (Wurbs 2005a, 2014) provides unique opportunities for comparative analyses of river flows and related quantities under natural and developed conditions for multiple major rivers with very different characteristics.

The case study analyses presented in this chapter include the following components. Analyses of 1940-2015 observed precipitation and reservoir evaporation rates indicate that these climatic variables have remained essentially stationary. Any long-term trends are hidden by great continuous variability. Significant and in some cases dramatic long-term alterations in observed gauged stream flows over the past several decades are evident for many river reaches. The characteristics of the flow increases and decreases differ greatly with location. Naturalized and regulated flows from the statewide water availability modeling system are employed to explore alterations in flow frequency statistics. Naturalized flows represent historical period-of-analysis (such as 1940-2015) river basin hydrology without human water development, regulation, and use. Regulated flows are the flows computed in the WAM simulation model based on combining historical period-of-analysis natural hydrology with specified conditions of water resources development, allocation, management, and use.

REVIEW OF PUBLISHED LITERATURE

A myriad of journal papers and other publications document investigations of the impacts of dams and reservoirs, water use, watershed land use changes, climate change, and other factors on stream flow along with analysis methods for assessing these impacts. Many studies deal specifically with either floods or droughts. Other studies address the full range of river flows. Some studies focus specifically on stream flow while others deal with other aspects of hydrology and/or water management. Some studies analyze flow changes without regard to cause, while other studies focus on the effects on flow resulting from specific causative factors or the effects of flow alterations on water management.

The numerous studies of alterations to river flows reported in the literature rely upon one or combinations of the following analysis strategies.

- trend analyses of observed flows at gauging stations with long periods-of-record
- statistical metrics for post versus pre-development sequences of observed flows
- precipitation-runoff modeling with watershed parameters that vary with post versus pre-development or with precipitation and other input that vary with future climate scenarios
- river/reservoir system modeling studies that simulate alternative conditions of water resources development, regulation, allocation, management, and use

Statistical Trend Analyses of Gauged River Flows

The U. S. Geological Survey (USGS) has applied least-squares linear regression, the Kendall tau test, and other standard trend analysis methods (Helsel and Hirsch 1992; McCuen 2003) to long series of daily, monthly, and/or annual stream flow data observed at gauging stations to detect long-term trends in low, high, and median flows for various rivers. Many studies, including several representative studies cited below, have focused on specific river systems, while other studies including several cited below have been nationwide.

USGS investigations of trends of flow alterations in specific river systems include the Chagrin River in Ohio (Koltun and Kunze 2002), Red River of Texas and Oklahoma (Smith and Wahl 2003), Puyallup River Basin of Washington (Sumioka 2004), St. Croix River in Wisconsin and Minnesota (Lenz 2004), Chesapeake Bay Basin (Langland, et al. 2004), and the Blackstone River Basin in Massachusetts and Rhode Island (Barbaro 2007).

Other USGS statistical trend analysis studies have been nationwide or for gauge sites scattered over large regions. Lettenmaier et al. (1994) investigated trends in monthly and annual stream flow at gauging stations across the United States. Lins and Slack (1999) examined trends using the non-parametric Mann-Kendall test for daily flows at selected frequency percentiles ranging from the annual minimum daily flow to annual maximum daily flow at 395 gauging stations located throughout the United States. They found that flows at low to median flow percentiles have increased across broad sections of the

United States but decreased in some areas. Systematic patterns were found to be less apparent for high flow percentiles. McCabe and Wolock (2002) examined annual minimum, median, and maximum daily flows at 400 gauges measured during 1941-1999 and found a noticeable increase in annual minimum and median daily stream flow around 1970 and a less significant pattern of increases and decreases in annual maximum daily flows.

The USGS investigated the effects of land and water management practices on 4,196 rivers located throughout the United States based on statistical regression analyses of gauged daily flow sequences, concluding that road density and number and size of dams were dominant metrics in explaining the causes of long-term trends of both flow increases and decreases (Eng et al. 2013). Agricultural development and wastewater discharges were also found to be closely associated with flow increases and decreases in some regions.

Several of the many investigators other than USGS scientists that have applied statistical methods to stream flow gauge records to quantify changes are noted as follows. Szilagyi (2001) describes application of statistical trend analyses and watershed precipitation-runoff modeling to investigate declines in flows over the past several decades in the Republican River of Kansas, Nebraska, and Colorado, concluding that the combined effects of agricultural activities and construction of dams and reservoirs have significantly reduced the flow of the river. Zhang and Schilling (2006) analyzed the trend of increasing base flow in the Mississippi River attributed to land use changes.

Analyses of century-long records of flows of the Athabasca River in Canada revealed slight, localized changes (Rood et al. 2015). Reductions in the flow of the Wei River in China are attributable to a combination of multiple factors (Gao et al. 2013). Huang et al. (2015) and Gao et al. (2012) analyzed flow regime changes resulting from constructing large dams on the Yangtze and Qingyi Rivers in China. Martinez-Fernández et al. (2013) performed trend analysis of flows of 74 near-natural headwater streams in Spain, finding significant trends of decreasing flows at a majority of the sites. Increases in evapotranspiration resulting from global warming and/or forest expansion over abandoned land were suggested as possible causes of the reduced stream flow. Djebou (2015) analyzed trends in 1961-2012 precipitation, stream flow, and land use parameters to assess the effects on flow of watershed changes. Hannaford (2015) reviewed studies reporting analyses of stream flow records throughout the United Kingdom noting that relatively small changes in flow regimes can be detected at some locations but attributing the changes to a specific causative driver is difficult.

Ye, Yang, and Kane (2003) analyzed long-term monthly flow records at gauging stations on the Lena River in Siberia to show the effects of climate change and human activities. Construction of a major dam accounted for most of the flow changes, reducing summer flows and increasing winter flows. Likewise, Peters and Prowse (2001) found that reservoir regulation on the Pease River in Canada greatly increased winter flows and decreased summer flows downstream. Singer (2006) explores the effects of dams on flows at different sites in the Sacramento River Basin of California.

Trimble and Weirich (1978), Bosch and Hewlett (1982), Stednick (1996), and Matheussen et al. (2000) are among the many investigators who have explored the effects of changes in forest cover on stream flow. Stankowski (1972) developed a quantitative index of urban land use characteristics based on population density to estimate impervious area as a determinant of changes in runoff. Dewalle and Swistik (2000) investigated gage records for 39 urbanizing and 21 rural regions in the U. S. to study the effects of climate change and urbanization on mean annual flows, finding that urbanization increases the mean annual flow roughly in proportion to cumulative changes in population density.

Environmental Flow Statistics

Many studies of river flow alterations have been motivated by environmental flow needs and issues. Acreman and Dunbar (2004), Poff and Zimmerman (2009), and Arthington (2012) review numerous methods for quantifying environmental flow needs reported in the literature involving field and office studies, computer models, and statistical methods.

Environmental flow studies often include statistical trend analyses similar to those noted in the preceding section. Another common alternative approach is to divide the record of daily flows at gauging stations into two periods representing pre-development and post-development conditions, for example before and after construction of a reservoir project. Statistical metrics for the pre-development and post-development periods of observed flows are compared to quantify the alterations resulting from development. Flow standards defining environmental requirements are also defined in terms of these flow statistics.

The Indicators of Hydrologic Alteration (IHA) is software package developed by the Nature Conservancy designed for performing ecologically-meaningful statistical analyses of daily flows (Richter et al. 1998, Matthews and Richter 2007, Nature Conservancy 2009). The IHA have been applied in many countries over many years. A hydrograph of daily observed flows is parsed into individual flow regime components. The parsed flow sequences representing various defined low, normal, and high flow conditions are analyzed to develop a large number of different relevant statistical metrics. Selected sets of statistics can be computed for pre-development and post-development sequences of daily observed flows. The IHA software also includes options for performing linear trend analysis computations.

Wurbs and Hoffpauir (2013) describe use of the Nature Conservancy IHA statistics in the development of environmental flow standards incorporated in the Texas WAM System that are based on flow regimes with subsistence flow, base flow, inbank high flow pulse, and overbank high flows pulse components. Pauls and Wurbs (2016) developed an alternative set of statistical metrics designed for application to many-year period-of-analysis sequences of daily naturalized and synthesized regulated flows from the WAM System for use in assessing flow alterations in terms of the subsidence, base, inbank high pulse, and over-bank high pulse flow regime components of environmental flow standards incorporated in the WAM System.

Watershed Precipitation-Runoff Models

The impacts of land use changes on stream flow are often assessed using watershed precipitation-runoff models (Singh 1995, Singh and Frevert 2006). In conducting urban stormwater management activities, cities and consulting firms routinely apply the HEC-HMS Hydrologic Modeling System (Hydrologic Engineering Center 2016) or other similar flood event models to estimate the impacts of land development on flood runoff. Continuous long-term watershed models such as the Soil and Water Assessment Tool (SWAT) may be applied to predict the effects of land use changes on the full range of flows including low flows (Arnold et al. 2012). Many other generalized watershed models have also been employed.

Watershed rainfall-runoff models have been routinely applied since the 1960s with rainfall and climatic data to assess the effects on hydrology of changes in land use represented by watershed parameters (e.g., Caldwell et al. 2012, Babar and Ramesh 2015, Crooks and Kay 2015). More recently, watershed models are applied in combination with climate models to predict the effects of global warning on hydrology (e.g., Steele-Dunne et al. 2008; Arnell and Gosling 2013, Arnell et al. 2014, Lee et al. 2014, Panagopoulos et al. 2015). Future precipitation and climate quantities predicted with a climate or global circulation model for a future greenhouse gas emission scenario are input to a watershed model to generate stream flow. In some cases, a water management model is combined with climate and watershed models (e.g., Wurbs et al. 2005, Islam and Gan 2014). The SWAT watershed rainfall-runoff modeling system has been particularly widely applied in these types of studies (Babar and Ramesh 2015, Mehdi et al. 2015, Devkota and Gyawali 2015).

The Soil and Water Assessment Tool (SWAT) was used to assess the impacts of agricultural activities on stream flow quantity and quality in the Hydrologic Unit Modeling of the United States (HUMUS) project accomplished for the Natural Resource Conservation Service (NRCS) of the U.S. Department of Agricultural by the Agricultural Research Service and Texas Agricultural Experiment Station of the Texas A&M University System (Srinivasan et al. 1995, Arnold et al. 1998, Arnold et al. 1999, Neitsch et al. 2002). Data are managed in SWAT through a geographic information system (Douglas-Mankin et al. 2010).

A GIS-based watershed parameter database developed for the HUMUS project that combines soil type and land use data to assign curve numbers (CN) was later adopted to estimate CN values for the numerous sub-watersheds included in the Texas WAM System watershed parameter files (Wurbs 2006).

Ryu (2015) applied SWAT to develop sequences of daily naturalized flows for use with the daily versions of WAMs from the TCEQ WAM System for several river basins in Texas. Application of SWAT with the TCEQ WAM System models for the Brazos and San Jacinto River Basins to investigate the impacts of climate change on water availability is discussed in the following section (Muttiah and Wurbs 2002, Wurbs et al. 2005).

Long-Term Changes in River Flows Due to Climate Change

The impacts of climate change associated with global warming on hydrology and water resources management have been addressed extensively in the literature. Major global, regional, and national assessments were reported by Frederick et al. (1997), van Dam (1999), Lattenmaier et al. (1999), Gleick (2000), National Assessment Synthesis Team (2000), Cluis and Laberge (2001), and the Intergovernmental Panel on Climate Change (2001, 2015). Wei et al. (2015) used bibliometrics to categorize 5,733 publications on climate change published from 1981 through 2013, noting the much accelerated growth in the number of publications since 2001. Chalecki and Gleick (1999) examined metadata for almost 900 references on the effects of climate change on hydrology and water resources in the United States. Many hundreds of papers and reports dealing with the impacts of global warming on hydrology and water resources worldwide have been published since 1999.

Climatic data for alternative future climate change scenarios are available from many different global circulation models. Many watershed models are available. Various combinations of global circulation models simulating climate processes and watershed models representing precipitation-runoff processes have been used to predict the effects of climate change on water resources in various regions of the world (e.g., Miller and Russell 1992, Brumbelow and Georgakakos 2001, Arora and Boer 2001, Matondo and Msibi 2001).

For example, Muttiah and Wurbs (2004) and Wurbs et al. (2005) describe assessments of potential impacts of global warming on water availability and supply reliability in the San Jacinto River Basin and Brazos River Basin of Texas. The Canadian Center for Climate Modeling and Analysis (CCCMA) global circulation model (Flato et al. 2000), SWAT watershed model, and TCEQ WAM System models for the San Jacinto and Brazos River Basins were combined to predict the impacts of global warming on water supply capabilities in the year 2050. Future temperature and precipitation predictions corresponding to a climate change scenario reflecting an increase in carbon dioxide concentration of 1% per year were obtained from the CCCMA. SWAT was applied to develop stream flows with and without the selected climate change scenario. These were used to adjust the stream flows and evaporation rates in the WAM simulation allowing assessments of changes in water supply reliabilities.

The future climate scenario generally resulted in decreased mean stream flows and greater variability. However, the effects on water availability vary significantly in different regions of the San Jacinto and Brazos River Basins and among water users. Impacts on individual water supply entities depend greatly on available reservoir storage capacity. All aspects of the climate, watershed, and water management components of the modeling process reflect approximations and uncertainties. However, the greatest uncertainty is probably associated with representing future climate using precipitation data from a global circulation model (Muttiah and Wurbs 2002, Wurbs et al. 2005).

Although focused on future climate change, Wurbs et al. (2005) also investigated flow change during 1900-1997 in the Brazos River Basin potentially attributable to climate change. Series of 1990-1997 monthly naturalized flows at seven locations were compiled based on 1940-1997 flows from the Brazos WAM and 1900-1939 flows developed by relatively minimal adjustments to gauged flows. A multiple-component trend analysis process was adopted that included segmentation, the Mann-Whitney test for step-wise trend analysis, and the Kendall test for linear trend analysis. The analyses of naturalized river flows indicated hidden but significant multiple-year cycles but no long-term trends during 1900-1997.

River/Reservoir System Management Models

Modeling and analysis of the management/operation of river/reservoir systems encompasses various hydrologic, physical infrastructure, environmental, and institutional aspects of river basin management. Dams and appurtenant structures are required to control highly fluctuating river flows to reduce flooding and develop reliable water supplies. Institutional mechanisms for allocating and managing water resources are integrally connected to constructed facilities. Management of the water and related land and environmental resources of a river basin integrates natural and man-made systems.

Wurbs (2005b, 2011) reviews the state-of-the-art of modeling river system management. An overview of the massive literature is combined with comparative analyses of generalized modeling systems that have been extensively applied by water management agencies in a diverse array of decision-support situations. *Generalized* means that a model is designed for application by users other than the original developers to river systems of various configurations and locations, rather than being site-specific customized to a particular system. Model-users develop input datasets for the particular river basin of interest. The comparative reviews provided by Wurbs (2005, 2011) include the following modeling systems: HEC-ResSim (Hydrologic Engineering Center 2013), MODSIM developed at Colorado State University (Labadie 2004, 2006), RiverWare developed at the University of Colorado (Zagona et al. 2001, 2006), CalSim developed by the California Department of Water Resources (Draper et al. 2004), and WRAP (Wurbs 2006a) discussed later in this chapter.

These generalized river/reservoir system management models are based on volume-balance accounting procedures for tracking the movement of water through a system of reservoirs and river reaches. The models compute reservoir storage contents, water supply withdrawals, hydroelectric energy generation, and river flows for specified water demands, system operating rules, and input sequences of stream inflows and net reservoir surface evaporation rates. The models simulate river flows for a specified scenario of development given flows for inputted flows for natural or some other defined condition. Flow and storage frequency and supply reliability analyses are performed with time series of simulation results.

THE STATE OF TEXAS AND ITS WATER AVAILABILITY MODELING (WAM) SYSTEM

The remainder of this chapter focuses on stream flow alterations in Texas. The Texas case study is representative of many regions of the world. The Texas experience illustrates (1) characteristics of river flows, (2) relative magnitudes and characteristics of impacts to flow resulting from various causative conditions and activities, and (3) modeling and analysis strategies for detecting and quantifying changes in river flows.

Texas is a large state located in the south-central United States that is representative of both the drier western and wetter eastern regions of the country. The state encompasses 263,000 square miles (682,000 km^2). Climate, geography, economic development, water use, and water management practices vary dramatically from the arid western desert to humid eastern forests, from sparsely populated rural regions to the metropolitan areas encompassing the cities shown in Figure 1. Mean annual precipitation increases from west to east from 8.0 inches (200 mm) to 57 inches (1,450 mm), with a statewide mean of 27.9 inches (709 mm).

The population of the state increased from 214,000 people in 1830 to 5,820,000 in 1930 to 14,200,000 in 1980 to 20,850,000 in 2000 and 25,390,000 in 2010 and is projected to increase to 29,510,000 by 2020 and 46,355,000 by 2060 (Texas Water Development Board 2017). Municipal and industrial water use is steadily increasing along with a leveling off of agricultural irrigation due largely to limited water availability. Instream flow for ecosystem preservation is a major concern. Declining groundwater supplies combined with population growth are resulting in intensified demands on surface water resources. Water supply was 70% from ground water and 30% from surface water sources during the 1960s and is presently supplied about equally from ground and surface water. The shifting to a greater reliance on surface water is expected to continue into the future.

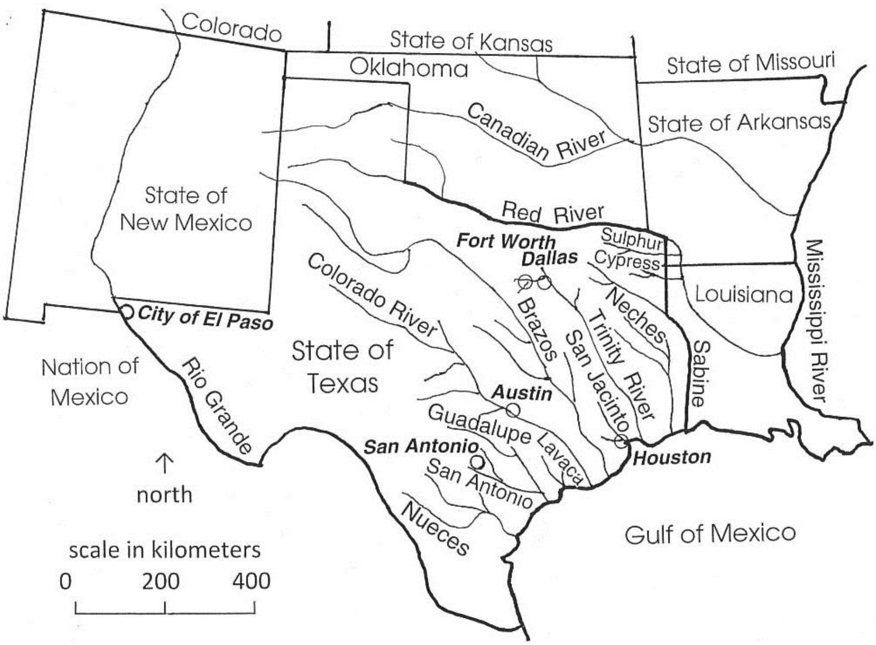

Figure 1. Map of Texas with major rivers, largest cities, and neighboring states.

Hydrology in Texas is extremely variable, subject to major flood events and multiple-year droughts along with seasonal and continuous fluctuations. The hydrologically most severe drought since before 1900 for most of the state began gradually in 1950 and ended in April 1957 with one of the greatest floods on record. Major droughts in the 1910's and 1930's were also multiple-year dry periods over large areas. More recent dry periods such as the 1996 drought that motivated enactment of the 1997 Senate Bill 1 were much more costly than earlier droughts due to population and economic growth. The 2008-2014 drought is comparable in hydrologic severity to the 1950-1957 drought in some western regions of the state. For more than half of Texas, 2011 had the smallest annual precipitation since the beginning of official precipitation records in 1895. On the other extreme, 2015 was one of the wettest years on record and included multiple major floods during the Spring and Fall. Flooding also occurred during the Spring 2016.

The Texas WAM System was authorized by the Texas Legislature in 1997 through legislation commonly known as Senate Bill 1. The Texas Instream Flow Program established by legislation called Senate Bill 2 enacted by the Texas Legislature in 2001 has resulted in extensive ongoing studies addressing environmental flow needs that are expected to continue for many more years into the future (Wurbs 2016). The Texas Legislature with its 2007 Senate Bill 3 created a systematic process for developing environmental flow standards and incorporating the flow standards into the WAM System. Environmental flow standards were established and incorporated into the WAMs for several priority river systems during 2010-2014 (Wurbs 2017). Quantifying alterations in river flows is fundamental to developing and applying the WAM System and also to establishing environmental flow standards.

Computer Software, Databases, and Technical Reports

The WAM System and databases maintained by water agencies in Texas, used along with other federally developed software and datasets, provide unique opportunities to investigate long-term changes in river flow characteristics and the various components of water budgets of multiple major river/reservoir systems with very different climate, hydrology, economic development, water resources development, and water management/use practices. Computer software, datasets, and technical reports discussed in the remainder of this chapter can be found at the websites listed in Table 1.

Table 1. Pertinent Websites

Texas Water Development Board (TWDB) Precipitation and Evaporation Databases http://www.twdb.texas.gov/surfacewater/conditions/evaporation/index.asp
Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) http://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html
Texas A&M University (TAMU) Water Rights Analysis Package (WRAP) https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm
Texas Water Resources Institute (TWRI) Technical Reports (TRs) http://twri.tamu.edu/publications/reports/
USACE Hydrologic Engineering Center (HEC) HEC-DSSVue http://www.hec.usace.army.mil/software/hec-dssvue/
United States Geological Survey (USGS) National Water Information System (NWIS) https://nwis.waterdata.usgs.gov/nwis

The English system of units is employed for essentially all water-related databases, modeling systems, and studies in Texas, similarly to the other states in the United States. English units are maintained without conversion to metric units in the following presentation for consistency with the original online databases, computer models, technical reports, and other sources of information.

The quantitative information and analyses presented in this following sections of this chapter are based on the following software and datasets accessible at the websites in Table 1.

- Databases maintained by the Texas Water Development Board (TWDB) of 1940-2015 monthly precipitation and 1954-2015 monthly reservoir evaporation rates for each of the 92 one degree quadrangles of a grid encompassing the state of Texas.
- Observed daily flow volumes at selected river gauges with long periods-of-record available through the National Water Information System (NWIS) maintained by the U.S. Geological Survey (USGS).
- The data storage system (DSS) developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) which has been incorporated in to the WRAP/WAM river/reservoir system management modeling system.
- Simulation results and associated frequency metrics generated with the WAM System maintained by the Texas Commission on Environmental Quality (TCEQ). The TWDB and USGS databases listed above are key hydrologic data sources for the WAM System.

Water Availability Modeling (WAM) System

The TCEQ WAM System consists of the Water Rights Analysis Package (WRAP) and WRAP input datasets for the river basins of Texas. WRAP combined with some variation of one of the TCEQ WAM System datasets is called a water availability model (WAM). The WRAP modeling system developed at Texas A&M University (TAMU) is generalized for application to river systems located anyplace in the world. WRAP is documented in detail by Wurbs (2013, 2015b, 2015c) and Wurbs and Hoffpauir (2015). Recent research and development at TAMU sponsored by the TCEQ to further expand the modeling system is focused on integrating environmental flow needs in comprehensive water management, updating hydrology input datasets, and various other modeling and water management issues.

The WRAP input datasets employed in the TCEQ WAM System were originally developed by the TCEQ, TWDB, other collaborating agencies, and contractors consisting of consulting firms and university research entities during 1997-2002 pursuant to the 1997 Senate Bill 1 (Wurbs 2005a, 2006b) and continue to be updated and expanded. The WAM system is routinely applied in Texas to support regional and statewide planning, administration of a water rights permit system, and other water management functions (Wurbs 2005a, 2014, 2015a). Wurbs and Zhang (2014), Pauls and Wurbs (2016), and other researchers have used the modeling system to explore various aspects of river system hydrology. This chapter employs the modeling system specifically to study the impacts of water resources development on river flows.

The WAMs simulate 3,450 permitted reservoirs, other constructed water control and conveyance facilities, two international treaties with Mexico, five interstate compacts, diversions and instream flow demands associated with over 6,200 water right permits, and return flows from both groundwater and surface water sources. WAM datasets are available for alternative water management scenarios. The authorized use scenario is based on the premise that all water right permit holders use the full amounts authorized in their permits. The current use scenario is based on current actual water management and use.

The TCEQ administers over 6,200 water right permits regulating storage and use of stream flow that are held by river authorities, municipal water districts, cities, irrigation districts, farmers, companies, and other entities and modeled in the WAMs. The 82 largest reservoirs with conservation storage capacities of 50,000 acre-feet (61.7 million m^3) or greater contain 91.8 percent of the total permitted conservation storage capacity of the 3,450 reservoirs in the water rights permit system. The WAMs do not include the many thousands of flood control reservoirs and stormwater detention structures, which do not require water right permits. The WAMs simulate only surface water management, but include return flows from all sources of supply including groundwater and also include channel losses due to infiltration and evapotranspiration. The WAM System is designed for assessing only water availability and supply reliability for water use in Texas but includes the effects of water use in Mexico and neighboring states on water availability in Texas.

WAM studies deal with historical period-of-record observed flows and simulated naturalized, regulated, and unappropriated flows at numerous sites throughout Texas. Naturalized flows are compiled by adjusting actual gauged flows to remove the impacts of water development and use. Regulated and unappropriated flows computed during a WAM simulation reflect changes to naturalized flows resulting from a specified scenario of water development and use. Regulated flows are physical flows considering the water development, allocation, management, and use information in the simulation input dataset. Unappropriated flows are available for further appropriation after all water right holders receive their allocated share. Regulated flows may be greater than unappropriated flows due to instream flow requirements at the site or commitments to other rights at downstream locations.

Hydrologic Engineering Center (HEC) Data Storage System (DSS)

The Hydrologic Engineering Center (HEC) of the U. S. Army Corps of Engineers (USACE) maintains a suite of generalized hydrologic, hydraulic, and water management simulation models that are applied extensively by numerous agencies and consulting firms throughout the United States and abroad. The HEC-DSS (Data Storage System) is used routinely with HEC simulation models and is also used with other non-HEC modeling systems including WRAP to manage time series input and output data. Multiple simulation models share the same data management and graphics software. Data is stored in DSS files in a direct access binary format. DSS files can be created, written to, and read only with software with DSS capabilities. Capabilities for creating and accessing DSS files are incorporated in software such as the WRAP programs by linking during compilation to routines from a HEC-DSS library of computer code developed by the HEC.

The HEC-DSS Visual Utility Engine (HEC-DSSVue) is an interface program for managing, editing, and graphing data in DSS files and performing statistical analyses and arithmetic operations. HEC-DSSVue is explained in detail by a user’s manual (Hydrologic Engineering Center 2009) available at the HEC website (Table 1) along with the software. DSS and HEC-DSSVue are designed for efficiently working with datasets of time series data, including extremely large datasets. HEC-DSSVue provides flexible capabilities for data storage and management, plotting graphs, statistical frequency analysis, and arithmetic operations. Data can be conveniently exchanged between HEC-

DSSVue and WRAP programs. HEC-DSSVue directly accesses the USGS NWIS website (Table 1) and other online data sources.

The WRAP simulation model and auxiliary programs store and access hydrology time series input data and time series simulation results in DSS files which are also accessed, displayed, and analyzed with HEC-DSSVue. DSS and HEC-DSSVue are integrated components of the WRAP modeling system. The data series discussed throughout the remainder of this chapter are stored and managed as DSS files.

River Systems of Texas

As shown in Figure 1, the rivers of Texas flow to the Gulf of Mexico or are tributaries of rivers that flow to the Gulf of Mexico. The 263,000 mile^2 (682,000 km^2) state is divided into the 15 major river basins and eight coastal basins delineated in Figure 2. The 254 counties of Texas are also delineated in the TWDB map. The 23 river basins are modeled in the TCEQ WAM System as 20 datasets which when combined with the generalized WRAP simulation model are called water availability models (WAMs). The Brazos WAM includes the San Jacinto–Brazos Coastal Basin as well as the Brazos River Basin. The Colorado WAM includes the Brazos-Colorado Coastal Basin as well as the Colorado River Basin. The GSA WAM includes both the Guadalupe and San Antonio River Basins. The other WAMs each model a single river basin.

The nine WAMs listed in Table 2 include ten of the 15 major river basins and two of the eight coastal basins shown in Figure 2. With the exception of the Sabine, the river basins in Table 2 are contained almost entirely within the state boundaries and flow directly into the Gulf of Mexico. The majority of the watersheds of the other five major river basins omitted from Table 2 are outside of Texas in neighboring states and Mexico. The quantities in Table 2 provide a general depiction of the hydrologic characteristics of these river basins. These quantities are derived from the precipitation and evaporation databases maintained by the TWDB and WAM system maintained by the TCEQ.

The watershed drainage areas in column 2 of Table 2 exclude areas lying outside of Texas. Additional areas of the Brazos and Colorado River Basins of 2,710 and 200 square miles, respectively, in New Mexico contribute essentially no flow to these rivers. The Sabine River Basin contains another 2,200 square miles in Louisiana in addition to the 7,570 square miles in Texas. The Brazos WAM basin area in Texas of 44,310 square miles includes 43,160 square miles in the Brazos River Basin and 1,150 square miles in the San Jacinto-Brazos Coastal Basin. The Colorado WAM basin area in Texas of 41,280 square miles includes 39,420 square miles in the Colorado River Basin and 1,860 square miles in the Brazos-Colorado Coastal Basin. The extreme upper basin areas of the Brazos and Colorado Rivers in the dry flat High Plains Region of New Mexico and Texas contribute essentially no runoff to the river systems.

Figure 2. Texas river basins as delineated by the TWDB.

Table 2. Hydrologic Quantities Characterizing Selected River Basins

1	2	3	4	5	6	7	8	9
	Basin	Mean	Naturalized Flow		Reservoirs			Mean
WAM	Area	Precip	at Basin Outlet		Number	Storage Capacity		Evap
	(mile^2)	(inch/yr)	(% Prec)	(ac-ft/yr)		(ac-ft)	(% Nat)	(inches)
Brazos	44,310	29.4	10.4	7,246,000	719	4,016,000	55.4	60.2
Colorado	41,280	24.5	5.79	3,119,000	489	4,710,000	151.	63.1
GSA	10,133	32.4	12.7	2,220,000	241	757,000	34.1	54.1
Lavaca	2,310	39.7	17.6	860,000	21	168,000	19.5	50.8
Neches	9,940	48.7	24.1	6,224,000	180	3,656,000	58.7	48.5
Nueces	16,700	24.8	2.93	648,000	125	960,000	148.	59.6
Sabine	7,570	47.8	34.4	6,633,000	213	6,262,000	94.4	50.9
San Jacinto	3,940	46.6	23.2	2,270,000	114	588,000	25.9	49.0
Trinity	17,910	39.4	17.6	6,630,000	697	7,356,000	111.	55.1

Note: 1.0 mile^2 = 2.59 km^2, 1.0 inch = 2.54 cm; 1.0 acre-feet = 1,234 m^3.

The mean annual precipitation depths falling on the watershed areas of column 2 are tabulated in column 3. The mean annual reservoir surface evaporation rates are tabulated in column 9. These precipitation and evaporation rates were computed from the TWDB databases for quadrangles of one degree latitude by one degree longitude, which have areas of about 4,000 square miles. Watersheds delineations were superposed on the quadrangles (Wurbs and Zhang 2014).

Mean annual precipitation varies dramatically from west to east across Texas. For example, the mean annual precipitation depth of 29.4 inches/year in Table 2 is averaged spatially over the Brazos River Basin, but the mean annual precipitation varies from 19 inches/year in the upper basin in and New Mexico to 45 inches/year in the lower basin near the Gulf of Mexico. The spatial variability of reservoir surface evaporation rates is significant but much less variable than precipitation. The average reservoir evaporation rates in the Brazos River Basins is 60.2 inches/year, ranging from 65 inches/year in the upper basin to 48 inches/year in the lower basin.

WAM naturalized flows represent natural conditions without human water development and use. The means of the WAM naturalized flow volumes at the basin outlets are shown in columns 4 and 5 in acre-feet/year and as a percent of the mean precipitation over the river basins from column 3. For example, the long-term means of naturalized flow volumes of the Brazos and Trinity Rivers discharging into the Gulf of Mexico are estimated to be about 10.4% and 17.6%, respectively, of the corresponding long-term mean of the volumes of precipitation falling of the Brazos and Trinity River Basins. The means of the annual naturalized flow volumes at the outlets of the Brazos and Trinity WAMs are equivalent to covering the watersheds to depths of 3.06 and 6.94 inches each year as compared to precipitation depths of 29.4 and 39.4 inches/year, respectively.

Information regarding the permitted reservoirs included in the WAMs is provided in columns 6, 7, and 8 of Table 2. The number of reservoirs and total conservation storage capacity in each WAM are listed in columns 6 and 7. The conservation storage capacity (column 7) is expressed in column 8 as a percentage of the annual naturalized flow volume (column 5) for comparison.

Stream flow is regulated by constructed reservoir projects which are integral components of river systems. Most of the total conservation and flood control storage capacity in Texas is contained in some number of the largest of the approximately 200 major reservoirs with more than 5,000 acre-feet of conservation storage capacity. The thousands of smaller reservoirs account for a relatively small portion of the total storage capacity. The quantities in Table 2 are for conservation storage capacity, which means primarily municipal, industrial, and agricultural water supply but also recreation, hydroelectric power generation, and other conservation purposes. Flood control and stormwater detention storage is not included in Table 2. The large flood control pools of the 30 federal reservoirs (including nine and eight USACE reservoirs in the Brazos and Trinity Basins), 2,000 smaller rural flood retarding structures constructed by the Natural Resources Conservation Service in Texas, and countless small urban stormwater detention basins are not reflected in Table 2.

The approximately 200 major reservoirs in Texas with water supply storage capacities of at least 5,000 acre-feet (6.17 million m^3) are all impounded by constructed dams. The 35 major reservoirs in operation in 1935 were relatively small water supply projects. The oldest reservoir began impoundment in 1900. Most of the present reservoir storage capacity in Texas was developed between 1935 and 1990.

Reservoir evaporation is a major component of river system water budgets. Based on WAM simulation studies, the long-term average of the statewide total volume of evaporation from the 3,450 reservoirs included in the TCEQ WAM System exceed estimates of the total annual 2010 municipal water supply diversions from all surface and groundwater sources statewide. Estimates of reservoir water surface evaporation rates also provide approximate maximum limits on evapotranspiration rates. The majority of the precipitation that falls to the ground is loss through evapotranspiration.

The hydrologic cycle is complex with human activities superimposed on natural processes. Precipitation is the source of stream flow. Most precipitation falling to the ground returns to the atmosphere through evaporation or transpiration prior to reaching the ocean as stream flow or subsurface flow. Precipitation replenishes soil moisture and groundwater and becomes surface runoff and stream flow. The following discussion of long-term changes in hydrology indicate that: (1) any long-term trends in rainfall that may have occurred during 1940-2015 are hidden by the great continuous rainfall variability, (2) stream flow is extremely variable throughout Texas, and (3) significant long-term changes in stream flow characteristics have occurred at some but not all locations but vary greatly between locations.

PRECIPITATION AND RESERVOIR EVAPORATION RATES

Precipitation and evaporation rates are key climatic variables driving stream flow. The Texas Water Development Board maintains datasets of monthly precipitation and reservoir surface evaporation depths from 1940 to the present for 92 one-degree quadrangles comprising a grid that encompasses the 682,000 km^2 state. However, reservoir evaporation rates prior to 1954 are not used due to inconsistencies in data compilation methods before 1954. The databases are updated annually. The number of gauging stations has varied over time, but in 2015 included 2,400 precipitation and 76 evaporation stations, most managed by the National Weather Service. The TWDB uses Thiessen networks in computing means for each of the 92 quads for each month. The monthly reservoir evaporation depths are estimated based on measurements from standard NWS evaporation pans and lake/pan multiplier coefficients that vary over the 12 months of the year and with location. These monthly precipitation and evaporation datasets have been converted to DSS files at TAMU and analyzed with HEC-DSSVue and WRAP programs to explore long-term climatic trends.

Statewide mean precipitation for each month for January 1940 through December 2015 is plotted in Figure 3. Statewide mean annual precipitation and the minimum and maximum two-month precipitation in each year of 1940-2015 are plotted as Figure 4. Corresponding reservoir evaporation depths are plotted in Figures 5 and 6.

The area-weighted 1940-2015 mean precipitation for the 92 one-degree quadrangles covering the state of Texas is 28.08 inches/year (713 mm/year). The mean precipitation for individual quads varies from 9.35 inches/year (33%

of the mean) in the extreme west increasing from west to east to 56.5 inches/year (201% of the mean) in southeast Texas. The statewide means of the monthly precipitation depths are plotted in Figure 3. The 1940-2015 statewide annual precipitation depth and maximum and minimum two-month depths each year are plotted in Figure 4. The maximum or minimum two-month depth is the total depth during the two consecutive months of each calendar (January-December) year that represents the maximum or minimum for that year. Precipitation is almost all rainfall. Infrequent snowfall and sleet melts quickly.

Linear regression statistics have been computed for the annual, two-month minimum, and two-month maximum precipitation depths for each of the 92 individual quadrangles as well as for these quantities spatially averaged for the entire state. A linear regression line through the 76 years of annual precipitation depths averaged over the entire state has a slope of 0.01125 inch/year (0.286 mm/year). The 1940-2015 trend slopes for total annual precipitation for the 92 individual quads are negative for 26 of the quads and positive for the other 66 quads.

The computed linear regression slopes for the annual, two-month minimum, and two-month maximum precipitation depths for the 92 individual quads and statewide averages are too small to conclude that any long-term trends are evident. Likewise, long-term trends are not apparent in plots of these time series data. Any trends that may have occurred are hidden in the great random variability exhibited by the rainfall.

These same types of analyses were also applied to reservoir evaporation rates. The area-weighted 1954-2015 statewide mean is 59.4 inches/year (1,510 mm/year). A linear regression line through the 62 years of annual evaporation depths averaged over the entire state has a slope of 0.0692 inch/year (1.76 mm/year). The 1954-2015 trend slopes for annual evaporation for the 92 individual quads are negative for 27 and positive for the other 65 quads.

Long-term trends in precipitation and evaporation are highly dependent on the period-of-analysis adopted. For example, as previously noted, a linear trend line through the 76 years of 1940-2015 annual precipitation depths averaged over the entire state has a slope of 0.01125 inch/year. The year 2015 is the wettest year during the 1940-2015 period-of-analysis. Omitting 2015, a linear trend line through the 75 years of 1940-2014 annual precipitation depths has a slope of −0.00302 inch/year. Thus, the addition of 2015 changes the slope from increasing to decreasing. Statewide precipitation during 2016 was higher than the 1940-2015 mean but much lower than during 2015.

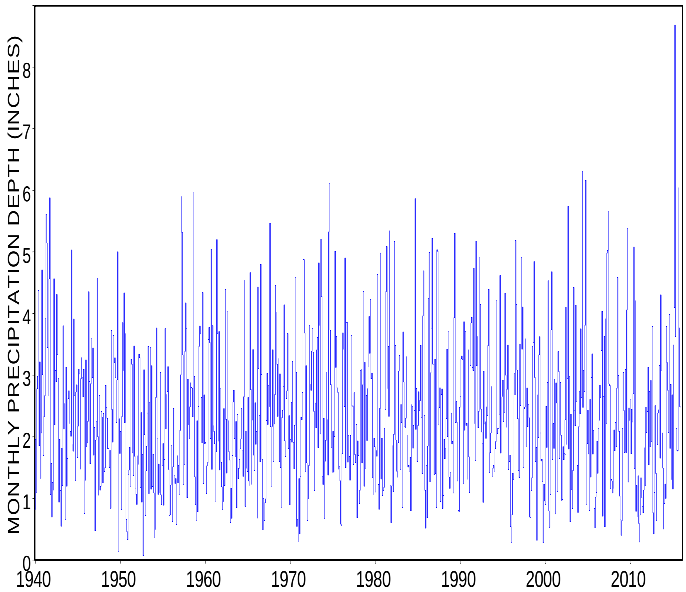

Figure 3. Monthly statewide mean precipitation during January 1940 - December 2015.

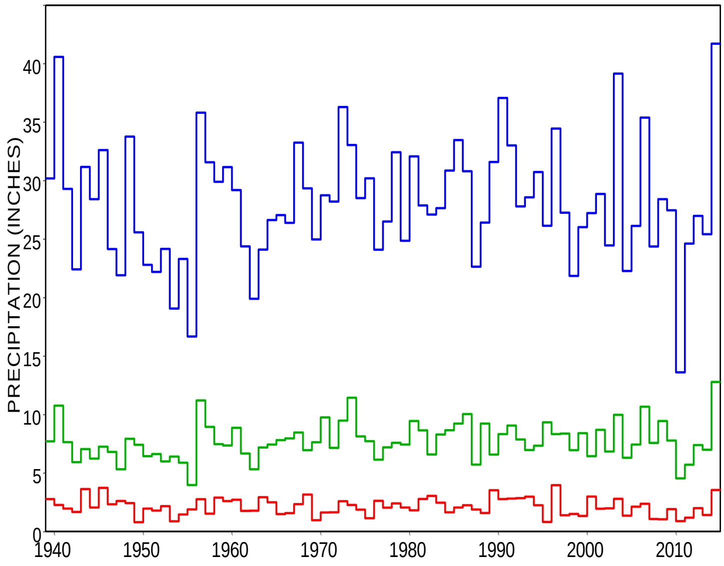

Figure 4. Annual total (top plot), two-month maximum (middle plot), and two-month minimum (bottom plot) precipitation depth in each year during 1940-2015.

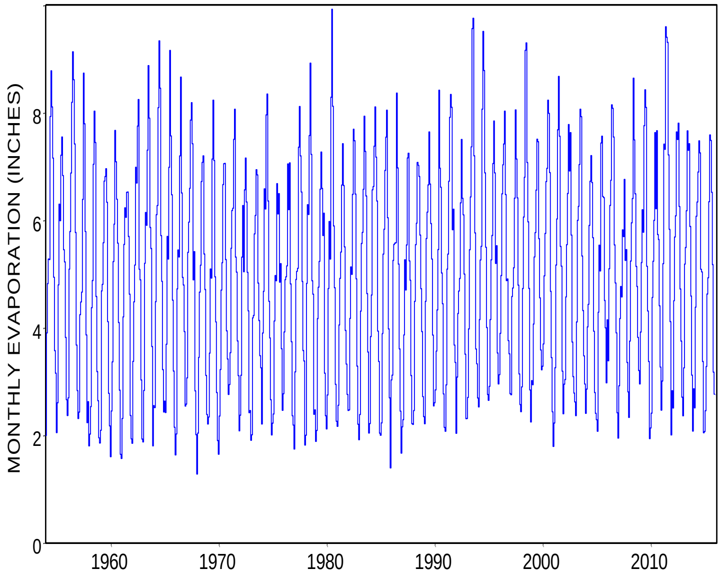

Figure 5. Monthly statewide mean reservoir evaporation rates during 1954-2015.

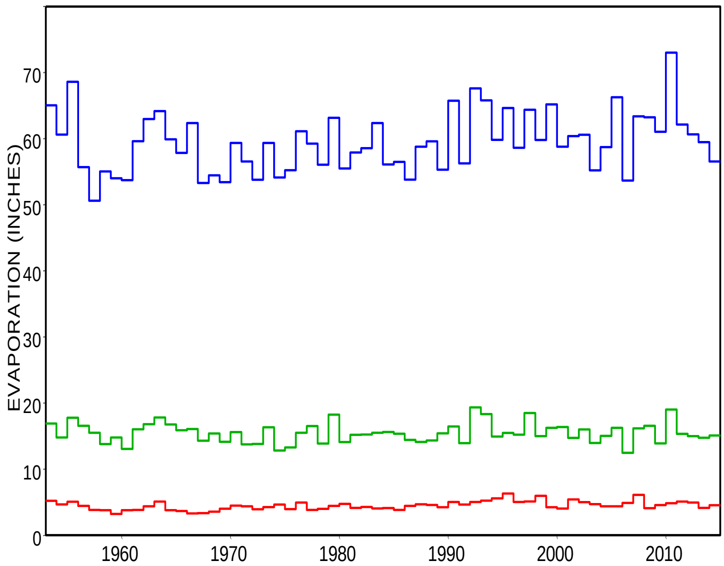

Figure 6. Annual total (top plot), two-month maximum (middle plot), and two-month minimum (bottom plot) reservoir evaporation depth in each year during 1954-2015.

Annual total, two-month maximum, and two-month minimum precipitation and reservoir evaporation depths are plotted in Figures 4 and 6. It is evident from these plots that trend analysis for different alternative sub-periods with lengths of thirty years or less could be selected that would yield very different positive and negative trend slopes.

The 1940-2015 and 1954-2015 linear regression metrics for the annual total, annual two-month minimum, and annual two-month maximum precipitation depths and reservoir surface evaporation depths for the 92 individual one-degree quadrangles and statewide averages are too small to conclude that any trends or long-term changes are evident.

OBSERVED RIVER FLOWS

Daily flows measured at numerous USGS gaging stations have been downloaded from the NWIS (Table 1) using HEC-DSSVue (Table 1) and stored as DSS files. HEC-DSSVue provides convenient time series plotting and statistical analysis capabilities. All of the time series plots in this chapter were created with HEC-DSSVue. The other WRAP programs access DSS files and provide statistical analysis options as well as capabilities for simulating river/reservoir system water resources development, allocation, management, and use.

Observed flows at about 500 USGS gauging stations were employed by the TCEQ, TWDB, and consulting engineering firms working for the agencies in developing naturalized flows for the original WAM hydrology datasets (Wurbs 2005a, 2006b). Many comparative analyses of observed and WAM synthesized flows have also been performed at TAMU over the past 20 years sponsored by the TCEQ, TWDB, and other agencies. The statistical analyses of various hydrologic variables reported by Wurbs and Zhang (2014) include analyses of observed flows at 35 selected USGS gaging stations on major rivers throughout Texas with records of at least 70 years. Other studies have focused on specific river basins.

Flows at all gauging station sites in Texas exhibit dramatic fluctuations including severe droughts and major floods along with continuous variability. Long-term trends of decreases in flows are evident at some gages, increases are evident at others, some exhibit both increases and decreases, and some sites exhibit no evident long-term changes. For sites with long-term changes, the characteristics of the changes may vary significantly between daily, monthly, and annual flows. Long-term changes may also differ greatly between high and low flows.

The Rio Grande and San Antonio River illustrate the extremes of dramatic decreases in flows versus dramatic increases in flows. Daily flows of the Rio Grande at the City of Brownsville are plotted in Figure 7. This gauge maintained by the International Boundary and Water Commission is located 49 miles (79 km) above the outlet of the Rio Grande at the Gulf of Mexico and 226 miles (363 km) below Falcon Dam. Annual flow means and the minimum monthly flow means during each year are plotted in Figure 8 for a USGS gauge on the San Antonio River at Falls City which is about fifty miles downstream of downtown San Antonio.

The gauge on the Rio Grande at Brownsville near the river outlet has a total watershed area of 356,000 square miles of which about half contributes little or no runoff to the river. Both high flows and low flows have decreased drastically over the past several decades at gauge sites along the lower Rio Grande. Construction of Falcon, Amistad, and other reservoir projects and intensive development of irrigated agriculture supplied by the Rio Grande since the early 1900s has dramatically decreased the flow of the river. Initial impoundment of the large multiple-purpose International Falcon and Amistad Reservoirs on the Rio Grande in 1953 and 1969 is evident in the flows plotted in Figure 7.

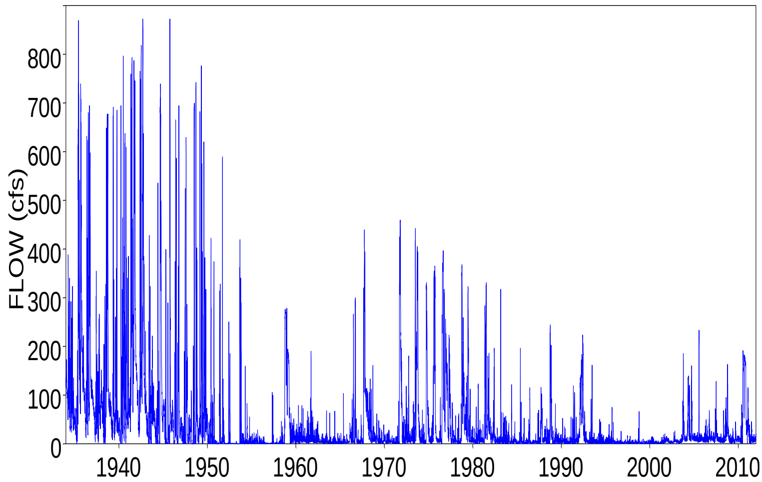

Figure 7. Daily Flows of Rio Grande at Brownsville from May 1933 through Dec 2011.

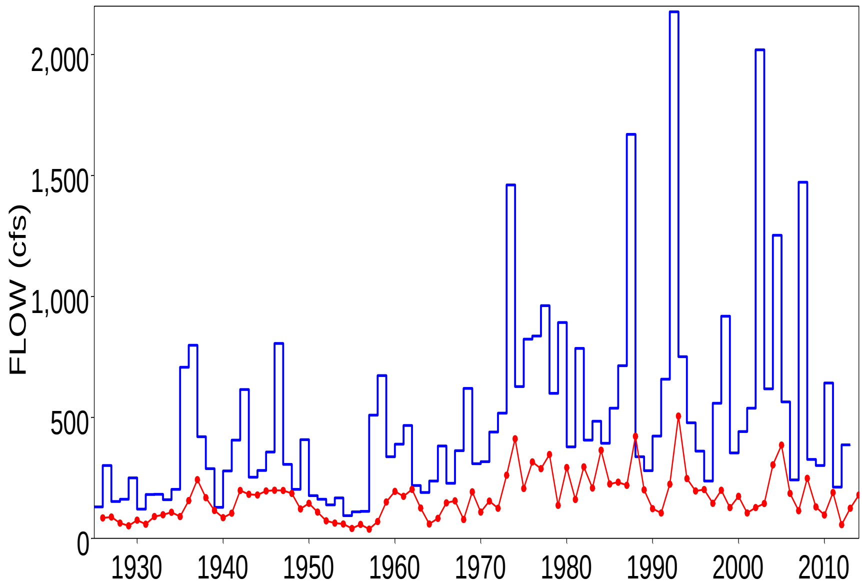

Figure 8. Annual Flows and the Minimum Monthly Flow Each Year of the San Antonio River at Falls City which is downstream of the City of San Antonio.

The Canadian River in northern Texas is another example of severe long-term flow reductions. Canadian River flow depletions are due largely to pumping groundwater for agricultural irrigation. The Canadian River flows from New Mexico across Texas to Oklahoma. Its drainage basin and neighboring river basins are over the Ogallala Aquifer, which supplies more water for irrigation in Texas than any other groundwater aquifer.

Both high flows and low flows have increased significantly over the past several decades at gauge sites on the San Antonio River below the City of San Antonio and Buffalo Bayou in Houston. Flows of the San Antonio River downstream of the City of San Antonio are plotted in Figure 8. Water supply for San Antonio is almost entirely from the Edwards Aquifer. Wastewater treatment plant effluents are discharged into the San Antonio River or its tributaries. Likewise, Houston is supplied primarily from local groundwater and surface water transported from the Trinity and San Jacinto Rivers. Wastewater treatment plant effluents are discharged into Buffalo Bayou and its tributaries which flow through the city to its confluence with the San Jacinto River near Galveston Bay. Increased rainfall runoff due to urbanization in the Houston and San Antonio metropolitan areas also contribute to increased stream flow.

High flows have decreased concurrently with increases in low flows number of sites throughout Texas, particularly downstream of major dams and reservoir projects. At other locations, changes are evident in either only high flows or only low flows. Long-term changes are not evident at all at many gauge sites on the rivers of Texas.

The plots of Figures 9 through 14 illustrate the extreme variability that characterizes stream flow in Texas. However, variability characteristics of low flows are masked to a significant degree in daily plots due to the scale necessary to plot high flows. Long-term trends in low flow characteristics may also be hidden. The averaging of flows inherent in plots of monthly and annual means also tends to hide low flow variability. Figures 11 and 14 include plots of the mean flow during the month in each calendar year that has the smallest mean flow. These annual minimum-month mean flow plots are designed to contribute to exploration of low flow trends. Flow units are cubic feet per second (1.0 cfs = 0.02832 cms).

Observed daily mean flows of the Brazos River at the USGS gage near the City of Waco are presented in Figures 9, 10, and 11 to highlight situations in which the long-term changes in flow characteristics may differ significantly between daily, monthly, and annual means. Likewise, the variability of instantaneous flow rates conceptually may be hidden in daily mean flow rates. The effects of large multiple-purpose reservoirs (Lakes Whitney, Waco, and Aquilla) with large flood control pools constructed by the U.S. Army Corps of Engineers upstream of the Brazos River at Waco gauge site during the 1950s-1980s are evident from the plot of daily flows in Figure 9. Flood control operations are based on making no reservoir releases that contribute to flows at the Waco gage exceeding 25,000 cfs (708 cms). The effects of the reservoir flood control operations are not evident in the plots of monthly flows or annual flows in Figures 10 and 11. Flood control storage attenuates flood hydrographs without reducing long-term flow volumes.

With a combined 2010 population of 6,372,000 people, the many cities of the Dallas-Fort Worth metroplex in the upper Trinity River Basin account for 25.3 percent of the population of Texas. Although most water use in the Trinity Basin is supplied by groundwater and surface water reservoirs within the Trinity Basin, water is also transported from reservoirs in adjoining river basins. The City of Houston in the San Jacinto River Basin has a pipeline from Lake Livingston on the lower Trinity River to supplement its other water supply sources.

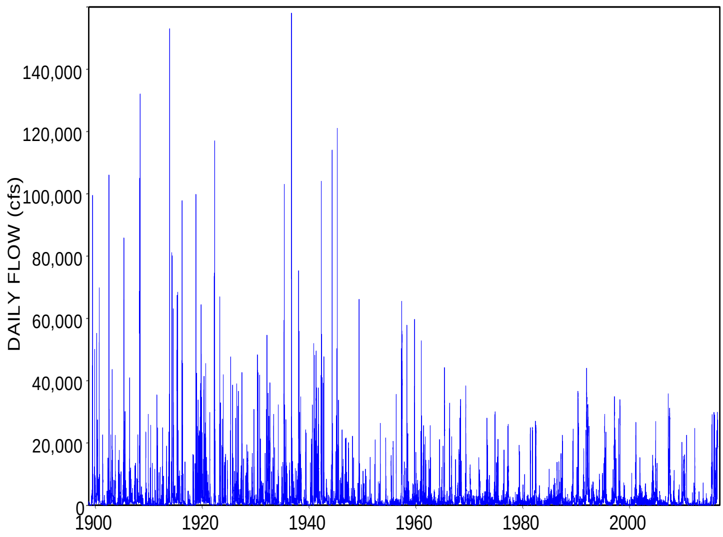

Figure 9. Daily flows of Brazos River at Waco during October 1, 1898 – July 4, 2016.

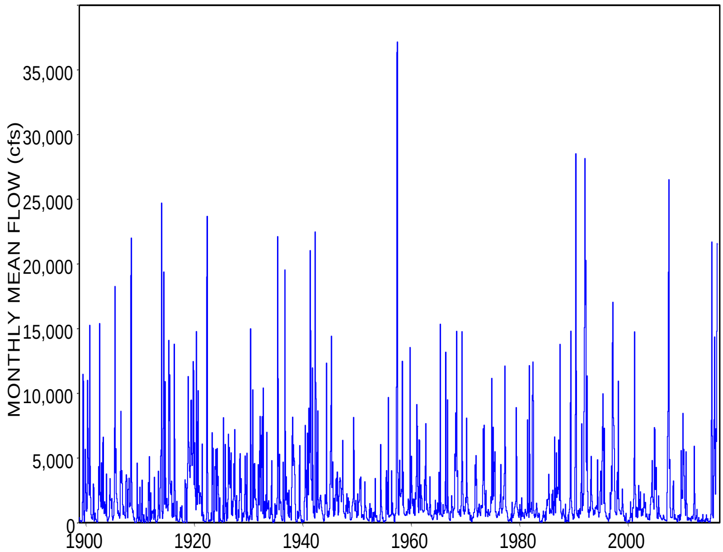

Figure 10. Monthly means of flows of the Brazos River at Waco from October 1898 through June 2016.

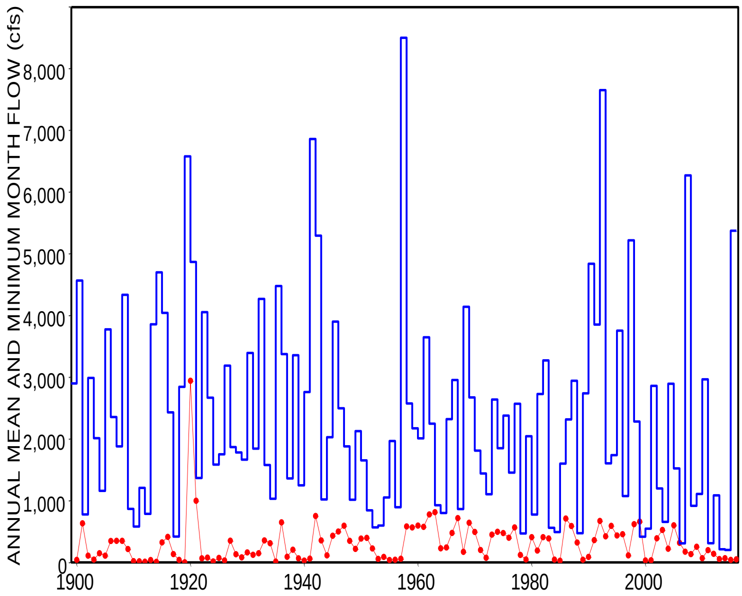

Figure 11. 1899-2015 Annual mean flow (solid line) and annual minimum monthly flow (dots) of the Brazos River at Waco.

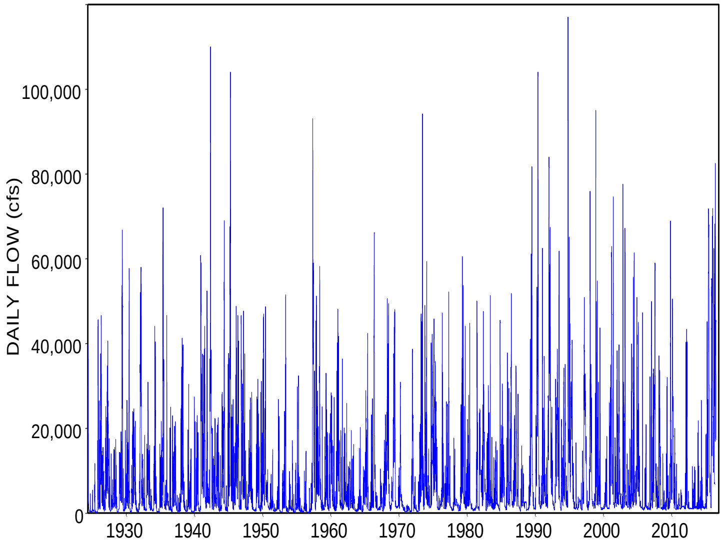

Figure 12. Daily gaged flows of Trinity River at Romayor during May 1924 – June 2016.

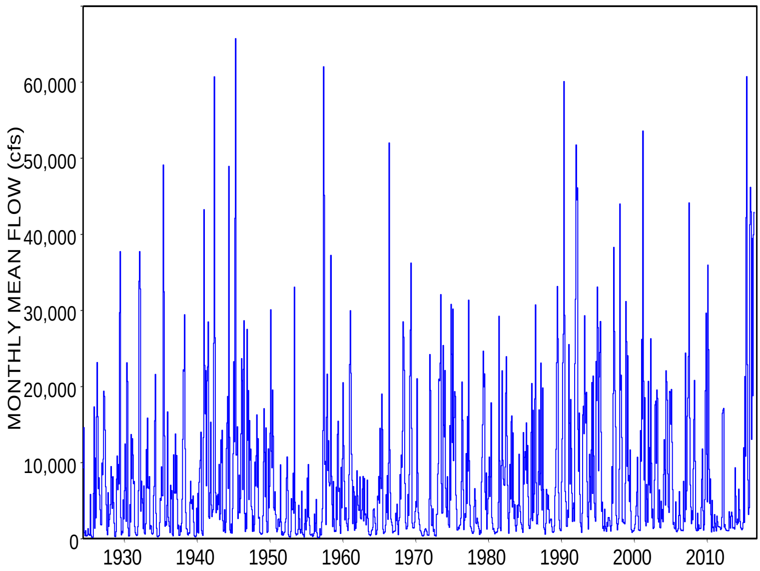

Figure 13. Monthly flows of the Trinity River at Romayor during May 1924 - June 2016.

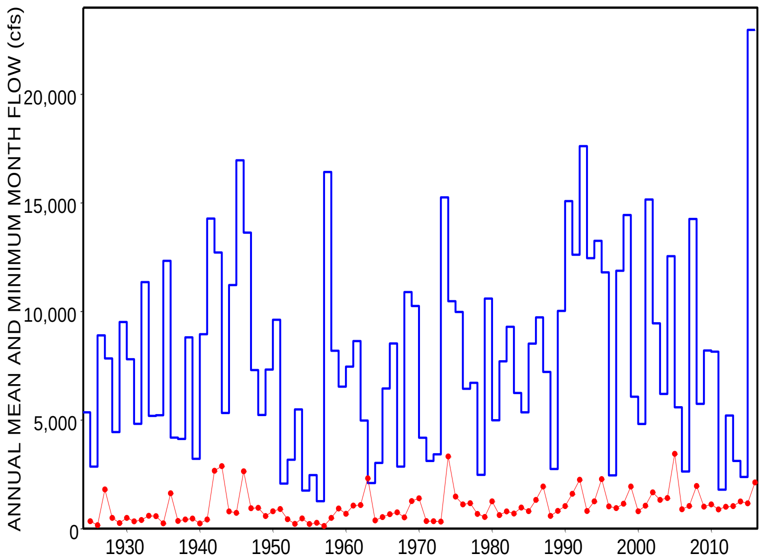

Figure 14. 1925-2015 Annual mean flow (solid line) and annual minimum, monthly flow (dots) of the Trinity River at Romayor.

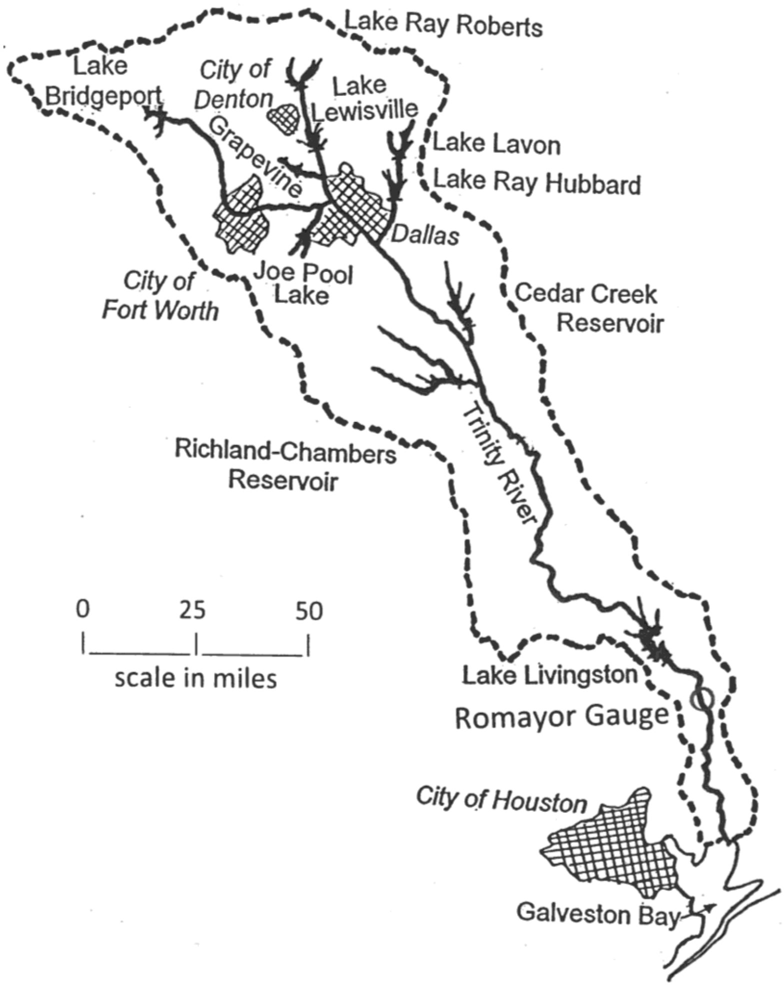

Figure 15. Trinity River Basin.

Observed mean daily and mean monthly flows at a gauging station on the Trinity River at the City of Romayor are plotted in Figures 12 and 13. The mean flow during each calendar year and the minimum monthly mean flow in each year during 1925-2015 at this site are plotted in Figure 14. This gauge shown in Figure 15 is 20 miles below Livingston Dam and 50 miles above Galveston Bay. The long-term mean of flows of the lower Trinity River at Romayor has been surprisingly stationary since the beginning of gauge records in 1924. Low flows have increased since the 1970s. At gauging stations on the three major branches of the Trinity River and their tributaries in the upper basin, reduction of flood peaks by Corps of Engineers flood control reservoirs and increases in low flows due to reservoir regulation and wastewater treatment plant discharges are evident. However, long-term trends of increases or decreases mean flows are not clearly evident at many sites. Changes or lack thereof vary between locations in the river system.

NATURALIZED AND SIMULATED REGULATED FLOWS

The generalized WRAP modeling system and WAM datasets combine river system hydrology and water management. Specified scenarios of water development, allocation, management, and use are combined in a WRAP/WAM simulation with an assumed repetition of historical natural hydrology represented by hydrologic period-of-analysis sequences of naturalized stream flows and reservoir net evaporation less precipitation rates.

Trinity River Basin Water Availability Model

The Trinity WAM is adopted here to illustrate the modeling strategy. The summation of the storage contents of all of the 697 reservoirs modeled in the authorized use scenario Trinity WAM is plotted in Figure 16. The simulation is based on the premise that all water right permit holders used the full amounts of water to which they are currently entitled and that water is managed by currently existing reservoirs and other constructed facilities. Hydrology is represented by 1940-2015 sequences of monthly naturalized stream flows and reservoir net evaporation less precipitation rates, which can optionally be disaggregated to daily quantities. Either a monthly or daily computational time step may be employed. The storage volumes plotted in Figure 16 were computed in a daily simulation.

In most WAM applications, storage levels in individual reservoirs and water supply reliability metrics for individual water right diversion targets are of interest. However, the Figure 16 plot of the total storage contents of all reservoirs provides an interesting basinwide drought index. The 1950-1957 drought is the most severe in terms of simulated reservoir drawdowns. The 2010-2014 drought is the second most severe. Both of these droughts are ended by extreme floods. People living in the Trinity River Basin have never experienced a drought as hydrologically severe as the 1950-1957 drought with present population, economic and water resources development, and water use demands, as modeled by the Trinity WAM.

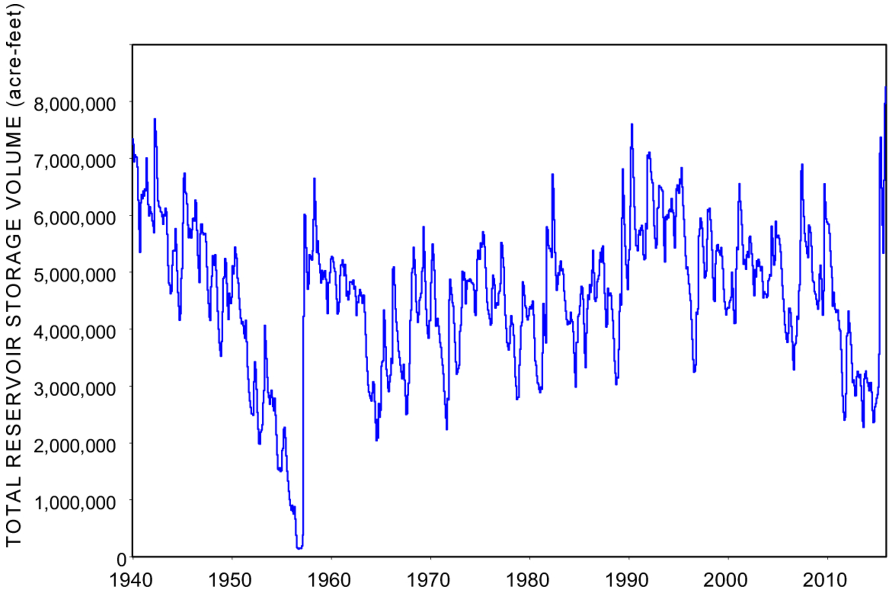

Figure 16. Simulated total storage volume in the 697 reservoirs in the Trinity WAM.

The 1940-2015 monthly naturalized flows in the Trinity WAM were developed by the TCEQ and its contractors based on adjusting observed flows at 40 gauge sites to remove historical effects of construction and operation of major reservoirs and water use driven by continual population growth that includes one of the most rapidly growing metropolitan areas in the U. S. during the past several decades. Regulated and unappropriated flows for each month or day of the 1940-2015 hydrologic period-of-analysis are computed by the simulation with water supply diversions and storage managed based on present conditions of development and water allocation.

The simulation begins with an input file of 1940-2015 naturalized monthly flows at 40 primary control points (gauge sites). The simulation model disaggregates monthly naturalized flows to daily using an input file of daily flow pattern hydrographs and distributes the naturalized flows to 1,360 ungauged sites using an input file of watershed parameters. The simulation model then computes sequences of 1940-2015 daily regulated and unappropriated flows at the 1,400 locations. Regulated and unappropriated stream flows reflect impacts of reservoirs and other constructed facilities, water allocation rules, and water supply diversion targets and return flows included in the WAM water rights input file. The simulated regulated flows represent the physical flows at a location. Unappropriated flows may be less than regulated flows due to environmental instream flow requirements at the same site and senior storage, instream flow, and diversion rights at downstream locations. Aggregated volumes of observed, naturalized, and simulated regulated flows at a location on the lower Trinity River are compared in Figure 17.

The observed monthly flows at the Romayor Gauge previously presented as Figure 13 were adjusted to derive naturalized flows for the Trinity WAM input dataset. The daily flows plotted in Figure 12 were adopted as daily flow pattern hydrographs to disaggregate monthly naturalized flow volumes to daily while preserving the monthly volumes. The resulting daily naturalized daily flows are plotted in Figure 18. Other alternative methods have also been employed to developed daily pattern hydrographs for the Trinity WAM and other WAMs for model control points on highly regulated streams.

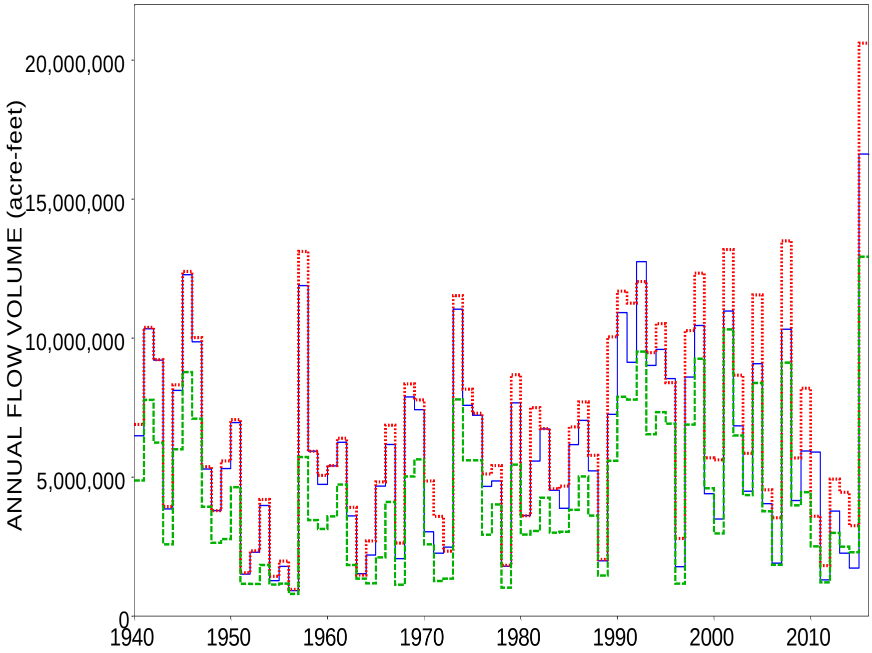

Figure 17. Annual volumes of naturalized (red dotted line), regulated (green dashed line), and observed (blue solid line) flows at the Romajor gauge.

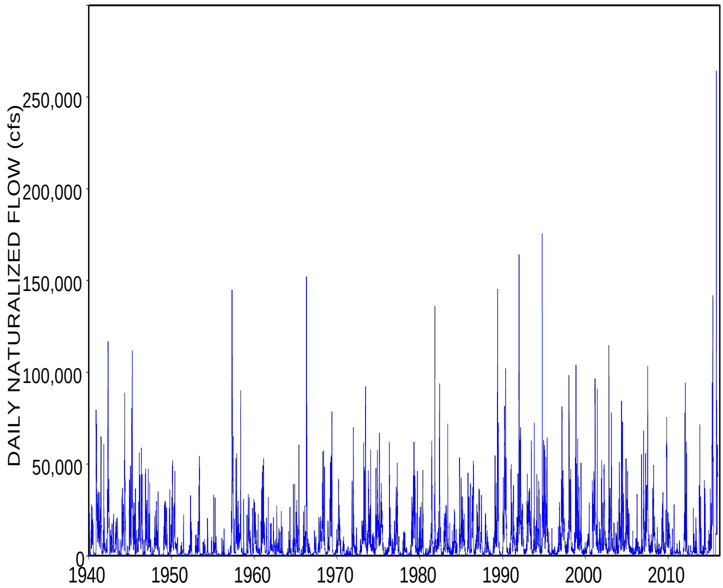

Figure 18. Daily naturalized flows at the Romayor gauge on the Trinity River.

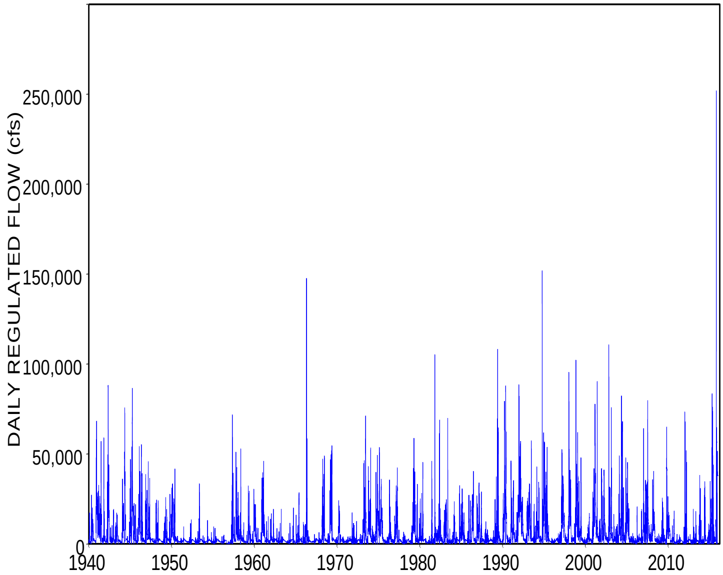

Figure 19. Daily regulated flows at the Romayor gauge on the Trinity River.

Table 3. Frequency Metrics in cfs for Naturalized Flows at Basin Outlets

		Standard	Exceedance Frequency				
WAM	Mean	Deviation	90%	75%	50%	25%	10%
Major River Basins							
Brazos	8,300	10,770	890	1,870	4,340	10,030	21,360
Canadian	300	653	10.9	26.5	86.2	292	706
Colorado	3,810	4,630	752	1,210	2,150	4,770	8,580
Cypress	2,310	2,960	25	237	1,070	3,360	6,430
Guadalupe-SA	3,020	3,780	385	939	1,730	3,740	7,100
Lavaca	1,190	2,050	46	136	367	1,240	3,450
Neches	8,540	9,670	717	1,650	4,700	12,500	21,930
Nueces	893	2,080	24.0	67.8	206	791	2,350
Red	13,950	15,080	2,100	3,950	8,720	19,210	31,070
Rio Grande	1,520	1,400	664	844	1,130	1,720	2,630
Sabine	9,070	9,320	953	2,120	5,680	13,630	22,070
San Jacinto	3,130	4,200	242	537	1,440	4,130	8,690
Sulphur	3,570	4,910	34	215	1,520	5,080	10,060
Trinity	8,330	10,380	427	1,520	4,200	11,400	22,070
Coastal Basins							
Colorado-Lavaca	540	890	14.1	53.0	208	604	1,550
Lavaca-Guadalupe	561	1,160	6.7	26.5	123	512	1,650
Neches-Trinity	1,590	1,950	75.6	336	950	2,180	3,640
Nueces- Rio Grande	413	1,360	0.0	0.0	0.0	131	1,100
San A-Nueces	780	2,570	9.2	19.8	63.2	403	1,720
Trinity-San Jacinto	250	388	13.8	31.8	93.6	305	685

Frequency Metrics for Naturalized and Regulated Flows at Basin Outlets

The frequency metrics in Tables 3 and 4 provide a comparison of river flows for current actual conditions of development versus natural undeveloped conditions. Metrics for monthly naturalized flows at the basin outlets for the 20 WAMs are tabulated in Table 3 in units of cubic feet per second (cfs). The corresponding metrics for WAM regulated flows are listed in Table 4 as a percentage of the metrics in Table 3, except regulated flows are shown in cfs if the naturalized flow quantity is zero. The quantities in Table 4 are created by dividing the naturalized flow quantities in Table 3 by the corresponded regulated flow quantities.

Table 4. Frequency Metrics for Regulated Flows at Basin Outlets as a Percentage of Naturalized Flows

Basin		Standard	Exceedance Frequency				
WAM	Mean	Deviation	90%	75%	50%	25%	10%
Major River Basins							
Brazos	79.3%	96.8%	1.1%	32.1%	54.2%	80.7%	89.3%
Canadian	59.0%	75.0%	47.4%	46.1%	55.6%	48.9%	50.1%
Colorado	54.9%	84.2%	0.08%	14.2%	26.0%	51.8%	63.9%
Cypress	87.9%	97.6%	7.0%	1.0%	64.1%	91.1%	96.3%
GSA	92.9%	98.3%	72.1%	78.6%	85.9%	93.3%	96.4%
Lavaca	93.7%	97.9%	99.5%	90.9%	81.5%	92.0%	97.0%
Neches	89.4%	101.2%	4.0%	31.4%	76.9%	92.8%	96.5%
Nueces	68.0%	71.3%	658.8%	255.4%	106.7%	51.4%	48.7%
Red	90.3%	97.3%	70.2%	72.0%	85.1%	94.5%	93.4%
Rio Grande	6.84%	42.58%	0.33%	0.66%	1.02%	1.41%	3.02%
Sabine	93.3%	101.5%	53.5%	61.4%	84.8%	95.8%	99.5%
San Jacinto	106.4%	96.1%	332.2%	183.7%	115.0%	95.8%	98.7%
Sulphur	96.9%	95.2%	737.0%	161.4%	95.8%	92.8%	96.2%
Trinity	82.0%	86.7%	247%	91.6%	67.7%	76.2%	81.4%
Coastal Basins							
Colorado-Lavaca	97.1%	98.9%	168.2%	107.3%	82.7%	94.0%	98.5%
Lavaca-Guad	102.6%	100.0%	302.5%	159.9%	112.9%	102.3%	100.8%
Neches-Trinity	91.4%	96.3%	112.6%	79.2%	86.4%	89.2%	93.2%
Nueces- Rio G	105.9%	99.1%	29.3cfs	33.5cfs	36.4cfs	116.4%	99.2%
San A-Nueces	100.0%	100.0%	101.6%	100.2%	100.2%	99.3%	100.0%
Trinity-San Jac	105.1%	99.5%	234.1%	148.7%	110.6%	101.0%	102.2%

The Trinity River Basin WAM is used as an example for interpreting Tables 3 and 4. Means, standard deviations, and quantities exceeded during specified percentages of the 912 months of the 1940-2015 Trinity WAM simulation are tabulated in Table 3. The mean and median (50% exceedance) naturalized flows at the Trinity River outlet are 8,330 cfs and 4,200 cfs. The corresponding mean and median regulated flows are 6,830 cfs and 2,840 cfs, which are 82.0 and 67.7 percent of the naturalized flows as shown in Table 3. The regulated flow level exceeded in 90 percent of the 912 months of the simulation is 247 percent of the naturalized flow amount of 427 cfs which has a 90 percent exceedance frequency. The 10% exceedance frequency regulated flow is 81.4% (Table 4) of the 10% exceedance frequency naturalized flow of 22,070 cfs (Table 3).

The comparative flow frequency metrics in Tables 3 and 4 are for model control points at gauging stations located near the river outlets. The WAMs can be employed to compute similar metrics for about 500 sites of gauging stations (primary control points) and over 10,000 ungauged sites (called secondary control points) located throughout Texas.

The differences between WAM naturalized and regulated flows represent the impacts of the reservoirs and other constructed facilities, water use demands, water allocation strategies, and management practices provided in the WAM water rights input file. The impacts of development on river flows vary greatly between the river basins and also between different sites in the same river basin. Impacts differ greatly across the range from low through median to extreme flood flows.

CONCLUSION

Investigations of alterations to river flows throughout the world have been reported in the literature. The impacts on river flows of dams and other water development projects and associated water use have been studied since the 1950s and before. The effects of urbanization and other land use changes have likewise been studied for several decades. Numerous analyses of the impacts on hydrology and water management of climate change due to global warming have been published since the 1990s. Modeling and analysis strategies include: trend analyses applied to observed flows; statistical analyses of observed flows during post and pre-development periods; watershed precipitation-runoff models with input parameters reflecting different conditions of watershed development or climate scenarios; and river/reservoir system models that simulate water development, control, management, and use. A number of representative publications are referenced in this chapter.

This chapter deals with changes in flow characteristics of major rivers at locations with watershed areas that range from hundreds to many thousands of square miles. The scope of the chapter does not include urban stormwater management for smaller watersheds, which is also an important subject that is extensively covered in the published literature.

Long-term stationarity or lack thereof is an important consideration in both water management and water availability modeling. The water availability modeling system and related databases maintained by water agencies in Texas provide excellent opportunities to explore long-term alterations in river flow characteristic as discussed in this chapter.

Precipitation and reservoir evaporation rate measurements provide information related to climate. Observed and simulated stream flow reflect the effects of water resources development/use and land use changes as well as climate.

River basin hydrology in Texas, like many other regions of the world, is characterized by extreme variability both spatially and temporally. The dramatic temporal variability in precipitation and stream flow throughout Texas includes multiple-year droughts and damaging floods as well as annual, seasonal, storm-event, and continuous fluctuations. Water resources development and management are governed largely by the necessity of dealing with the extremes of floods and droughts. Large volumes of reservoir storage are essential. Numerous reservoir projects have been constructed in Texas, most since the 1940′s, in response to dramatic population and economic growth and ever growing water demands.

Long-term changes in precipitation during 1940-2015 are not apparent in the analyses presented in this chapter. Likewise, long-term trends in reservoir evaporation rates are not evident. Any trends that may have occurred are hidden in the continuous high variability.

Analyses of observed precipitation, evaporation rates, and stream flow are sensitive to the length of the period-of-analysis. For example, significant trends of annual precipitation increases and decreases have occurred over different ten to twenty year sub-periods of the much longer periods-of-record analyzed in this chapter but not over the entire records. As another example, shortening the 1940-2015 period-of-analysis adopted in the WAM simulation studies to 1958-2009 would exclude consideration of the 1950-1957 and 2010-2014 droughts and the extremely wet 2015, which are very important to the hydrologic history of Texas and the analyses presented in this paper.

WAM naturalized flows exhibit essentially no noticeable long-term trends, indicating that changes in flow characteristics are due primarily to the past water development and use reflected in the computational process of adjusting observed flows to obtain naturalized flows. Long-term changes in river flow characteristics are quantified by comparing WAM homogeneous regulated flows for present conditions versus natural condition flows.

Flow characteristics of Texas river systems are explored through comparative analyses of observed, naturalized, and simulated regulated flows. Flows have changed significantly at many locations on the rivers of the state due to water resources development and use, but many other sites have experienced little if any detectable long-term alterations. While some sites have experienced increases in flows, other locations have had dramatic decreases in flows. Long-term changes in daily flows may differ greatly from changes in monthly and annual flows at the same location. Changes in low flow characteristics are very different than changes in flood flows.

The most dramatic decreases in river flows over the past century have resulted from extensive development of irrigated agriculture in dry western regions of the state. Reductions of peak flows of major floods by the thirty large Corps of Engineers flood control reservoirs are evident, with the attenuation being most pronounced immediately below the dams and less pronounced with distance downstream. The effects of cities on river flows are a complex combination of flow decreases due to water supply diversions and flow increases due to wastewater treatment plant discharges of water supplied from surface reservoirs and groundwater aquifers and both increases and decreases due to land use changes and associated stormwater management endeavors. Combinations of decreases in high flows and increases in low flows are found in many river reaches throughout the state.

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BIOGRAPHICAL SKETCH

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Dr. Wurbs has served on the faculty of Texas A&M University since 1980. He teaches graduate, undergraduate, and continuing education courses in water resources engineering, water resources systems planning and management, hydraulics, and hydrology and has been recognized with a number of teaching awards. His research over the past forty years has focused on various aspects of river/reservoir system management and related computer-based decision support. He and his graduate student research assistants developed over the past twenty years and continue to expand the generalized Water Rights Analysis Package (WRAP) modeling system described in the chapter. His WRAP-related research and development has been sponsored the Texas Commission on Environmental Quality, Texas Water Development Board, Texas Water Resources Institute, U.S. Department of Interior, U.S. Army Corps of Engineers, and U.S. Department of Energy. The modeling system is routinely applied by water agencies and consulting engineering firms, has significantly contributed to water management in Texas, and has been applied in several other countries.

Professional Appointments:

Civil Engineer and Program Manager, Water Resources Development Program, U.S. Army Corps of Engineers Fort Worth District (May 1971 to August 1980)

Arthur McFarland Endowed Professorship, Professor, Associate Professor, Assistant Professor, Zachry Department of Civil Engineering, TAMU (August 1980 to present)

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Associate Director for Engineering, Texas Water Resources Institute, TAMU (August 2007 to August 2012)

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Publications from the Last 3 Years:

R. A. Wurbs, "Incorporation of environmental flows in water allocation in Texas," *Water International*, Journal of the International Water Resources Association, Taylor & Francis, Vol. 42, Issue 1, January 2017.

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