The Handbook of Environmental Chemistry 25
Series Editors: Damià Barceló · Andrey G. Kostianoy

Tamim Younos
Caitlin A. Grady *Editors*

Climate Change and Water Resources

Springer

The Handbook of Environmental Chemistry

Founded by Otto Hutzinger

Editors-in-Chief: Damià Barceló • Andrey G. Kostianoy

Volume 25

The Handbook of Environmental Chemistry
Recently Published and Forthcoming Volumes

Climate Change and Water Resources
Volume Editors: T. Younos and C.A. Grady
Vol. 25, 2013

Emerging Organic Contaminants in Sludges: Analysis, Fate and Biological Treatment
Volume Editors: T. Vicent, G. Caminal, E. Eljarrat, and D. Barceló
Vol. 24, 2013

Global Risk-Based Management of Chemical Additives II: Risk-Based Assessment and Management Strategies
Volume Editors: B. Bilitewski, R.M. Darbra, and D. Barceló
Vol. 23, 2013

Chemical Structure of Pelagic Redox Interfaces: Observation and Modeling
Volume Editor: E.V. Yakushev
Vol. 22, 2013

The Llobregat: The Story of a Polluted Mediterranean River
Volume Editors: S. Sabater, A. Ginebreda, and D. Barceló
Vol. 21, 2012

Emerging Organic Contaminants and Human Health
Volume Editor: D. Barceló
Vol. 20, 2012

Emerging and Priority Pollutants in Rivers: Bringing Science into River Management Plans
Volume Editors: H. Guasch, A. Ginebreda, and A. Geiszinger
Vol. 19, 2012

Global Risk-Based Management of Chemical Additives I: Production, Usage and Environmental Occurrence
Volume Editors: B. Bilitewski, R.M. Darbra, and D. Barceló
Vol. 18, 2012

Polyfluorinated Chemicals and Transformation Products
Volume Editors: T.P. Knepper and F.T. Lange
Vol. 17, 2012

Brominated Flame Retardants
Volume Editors: E. Eljarrat and D. Barceló
Vol. 16, 2011

Effect-Directed Analysis of Complex Environmental Contamination
Volume Editor: W. Brack
Vol. 15, 2011

Waste Water Treatment and Reuse in the Mediterranean Region
Volume Editors: D. Barceló and M. Petrovic
Vol. 14, 2011

The Ebro River Basin
Volume Editors: D. Barceló and M. Petrovic
Vol. 13, 2011

Polymers – Opportunities and Risks II: Sustainability, Product Design and Processing
Volume Editors: P. Eyerer, M. Weller, and C. Hübner
Vol. 12, 2010

Polymers – Opportunities and Risks I: General and Environmental Aspects
Volume Editor: P. Eyerer
Vol. 11, 2010

Chlorinated Paraffins
Volume Editor: J. de Boer
Vol. 10, 2010

Biodegradation of Azo Dyes
Volume Editor: H. Atacag Erkurt
Vol. 9, 2010

Water Scarcity in the Mediterranean: Perspectives Under Global Change
Volume Editors: S. Sabater and D. Barceló
Vol. 8, 2010

Climate Change and Water Resources

Volume Editors: Tamim Younos · Caitlin A. Grady

With contributions by

K.M. de Beurs · Y.-s. Chen · S.B. Dessu · M.H.I. Dore · G. El-Afandi · M. Elshemy · E.S. Geller · C.A. Grady · L. Grossman · G.M. Henebry · L. Jiang · S. Lawson · L. Li · X.-h. Li · E. Lioubimtseva · A.M. Melesse · T. Noreldin · S. Ouda · T.E. Parece · P. Simcisko · R.G. Singh

Springer

Editors
Dr. Tamim Younos
The Cabell Brand Center for Global Poverty and Resource Sustainability Studies
Salem, VA, USA

Dr. Caitlin A. Grady
Purdue University
Ecological Sciences and Engineering Program
West Lafayette, IN, USA

The Handbook of Environmental Chemistry
ISSN 1867-979X ISSN 1616-864X (electronic)
ISBN 978-3-642-37585-9 ISBN 978-3-642-37586-6 (eBook)
DOI 10.1007/978-3-642-37586-6
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013941863

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

The Handbook of Environmental Chemistry Also Available Electronically

The Handbook of Environmental Chemistry is included in Springer's eBook package *Earth and Environmental Science*. If a library does not opt for the whole package, the book series may be bought on a subscription basis.

For all customers who have a standing order to the print version of *The Handbook of Environmental Chemistry,* we offer free access to the electronic volumes of the Series published in the current year via SpringerLink. If you do not have access, you can still view the table of contents of each volume and the abstract of each article on SpringerLink (www.springerlink.com/content/110354/).

You will find information about the

– Editorial Board
– Aims and Scope
– Instructions for Authors
– Sample Contribution

at springer.com (www.springer.com/series/698).

All figures submitted in color are published in full color in the electronic version on SpringerLink.

Aims and Scope

Since 1980, *The Handbook of Environmental Chemistry* has provided sound and solid knowledge about environmental topics from a chemical perspective. Presenting a wide spectrum of viewpoints and approaches, the series now covers topics such as local and global changes of natural environment and climate; anthropogenic impact on the environment; water, air and soil pollution; remediation and waste characterization; environmental contaminants; biogeochemistry; geo-ecology; chemical reactions and processes; chemical and biological transformations as well as physical transport of chemicals in the environment; or environmental modeling. A particular focus of the series lies on methodological advances in environmental analytical chemistry.

Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last three decades, as reflected in the more than 70 volumes of *The Handbook of Environmental Chemistry,* there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry,* the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of*

Environmental Chemistry provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Editors-in-Chief

Volume Preface

Climate change issues are broad and complex. This book does not present detailed arguments about climate change science or climate change models and scenarios. These arguments are well documented in IPCC reports and many other documents. However, a few chapters in this book present overviews of climate change science to set the stage for work presented in that chapter. Each chapter provides numerous reference citations to support scientific arguments and to lead the curious reader to more detailed information.

This book opens only a small window through which to view the world of climate change. The vulnerability of water resources to effects of climate change is the subject in view from this window. The book presents discussions of climate change models and scenarios, and exposes uncertainties and data deficiencies that affect the reliability of predictions about the consequences of climate change on water resources. Furthermore, this book provides an overview of climate change adaptation and mitigation strategies from water resources availability and water use perspectives.

Themes and issues discussed in this book include the following: (1) the applications and limitations of climate change models and scenarios, particularly those related to precipitation projection which is the critical factor for managing water resources; (2) the potential impacts of climate change on water resources including water quality; (3) the potential impacts of climate change on crop production and adaptation strategies for crop production; and (4) case studies of climate change mitigation strategies, particularly water use and conservation measures for reducing the carbon footprint of water consumption.

This book contains nine chapters. Chapters “Projecting Future Climate Scenarios for Canada Using General Circulation Models: An Integrated Review,” “Evaluation and Comparison of Satellite and GCM Rainfall Estimates for the Mara River Basin, Kenya/Tanzania,” and ”Projected Future Precipitation Scenarios for a Small Island State: The Case of Mauritius” focus on the critical issue of precipitation projections. Chapter “Climate Change Impacts on Water Resources in Semiarid Regions: Case Study of Aswan High Dam Reservoir” presents a case study of the climate change impact on water resources in semiarid regions of North Africa. Chapters “Modeling Climate Change Impacts and Adaptation Strategies for Crop Production in Egypt: An Overview” and “Grain Production Trends in Russia, Ukraine, and Kazakhstan in the Context of the Global Climate Variability and

Change" focus on the climate change impact on crop production and adaptation strategies for food security. Chapters "Mitigating Climate Change in Urban Environments: Management of Water Supplies," "The Impact of Urban Water Use on Energy Consumption and Climate Change: A Case Study of Household Water Use in Beijing," and "Reducing Carbon Footprint of Water Consumption: A Case Study of Water Conservation at a University Campus" discuss issues and case studies related to water use and conservation and climate change mitigation. A brief outline of each chapter, in order of its appearance, is provided below.

In the chapter "Projecting Future Climate Scenarios for Canada Using General Circulation Models: An Integrated Review," Dore and Simcisko provide an overview of the General Circulation Models (GCMs) and "downscaling" techniques which can improve model resolution at the regional level. The authors discuss available literature on projections of precipitation and stream flow over the next 100 years in Canada using several GCMs. The authors conclude that changes in the Canadian climate are projected to occur under all scenarios and with all models. Although climate change is projected over the entire country, the northern and western parts of Canada may be affected most severely.

In the chapter "Evaluation and Comparison of Satellite and GCM Rainfall Estimates for the Mara River Basin, Kenya/Tanzania," Dessu and Melesse address studies in data-scarce regions of the world where satellite rainfall estimates (RFEs) and rainfall outputs from GCMs are increasingly used, but where the reliability of data sources is seldom verified with observed data prior to use. Authors introduce the application of simple evaluation techniques to assess the potential of RFE and GCM outputs as potential rainfall information sources with application in the Mara River Basin of Kenya and Tanzania. They conclude that, in general, RFE and GCMs are promising sources of information, but refining the products with much-improved algorithms is essential.

In the chapter "Projected Future Precipitation Scenarios for a Small Island State: The Case of Mauritius," Dore and Singh address the impact of climate change in small island countries which are highly sensitive to changes in climate. As a case study, the authors applied four of the IPCC's Fourth Assessment GCMs to produce precipitation projections for the next 90 years in Mauritius, a small island country, situated about 1,100 km east of the mid-Madagascar. The results show that in Mauritius the net annual precipitation is likely to decline, historically wet months are likely to become even wetter, and dry months could become even drier in the future. Due to limited financial resources, Mauritius, like many small island states, may be unable to expand current water storage facilities in order to adapt to the expected impacts of future climate change. Hence, innovative ways of managing water resources will be critical not only for the water needs of the local population but also for the needs of the growing tourism-based economy.

In the chapter "Climate Change Impacts on Water Resources in Semiarid Regions: Case Study of Aswan High Dam Reservoir," Elshemy addresses climate change impacts on water resources in semiarid regions, particularly in Egypt. As a case study, the author uses climate change models and scenarios to study the impact of climate change on hydrodynamics and water quality of Lake Nubia which is located in the southern part of Aswan High Dam Reservoir. The hydrodynamic characteristics studied include water surface levels, evaporative water losses, and reservoir thermal structure. The water quality parameters of the study include pH, dissolved oxygen, chlorophyll-a, orthophosphate, nitrate–nitrite, ammonium, total dissolved solids, and total suspended solids. The results show that hydrodynamic and water quality characteristics of Lake Nubia will be significantly impacted by projected climate changes. The author identifies a critical need for developing a regional climate change model for the Nile Basin and acquiring long-term records of hydrodynamic and water quality characteristics of the Aswan High Dam Reservoir for detailed investigation of climate change impacts.

In the chapter "Modeling Climate Change Impacts and Adaptation Strategies for Crop Production in Egypt: An Overview," Ouda et al. address the climate change impact on crop production and the need for developing adaptation strategies to reduce the risk of future climate change. The authors introduce studies that highlight the importance of using climate change models to quantify the risk on wheat and maize production in Egypt. Field experimental data from case study sites located in four geographically different Egyptian regions and a crop simulation model output are incorporated in a climate change model to assess the effect of climate change scenarios and adaptation strategies on wheat and maize production. Results show that the yields of both crops will decline under future climate change scenarios, and the levels of decline depend on geographic location, soil type, and irrigation method. The authors conclude that it is necessary to improve adaptation strategies to present-day climate variability in order to reduce vulnerability to extreme events that may occur in the future.

In the chapter "Grain Production Trends in Russia, Ukraine, and Kazakhstan in the Context of the Global Climate Variability and Change," Lioubimtseva et al. discuss complex interactions between climate change and other factors and note that global grain production is highly sensitive to a combination of internal and external factors, such as climate variability, water resources, land-use changes, institutional changes, and global economic trends. The authors report studies on grain production potential in Russia, Ukraine, and Kazakhstan based on agroecological models driven by climate change scenarios and land change analysis. Results suggest that in these countries, a combination of winter temperature increase, extended growing season, and CO_2 fertilization could increase water availability and land suitability resulting in higher crop yields. However, the authors note that projections based on biophysical modeling alone should be considered with caution as they do not take into account regional socioeconomic and political factors. Furthermore, the authors state that due to the cross-scale contingent dynamics of coupled human and natural systems, it is critical to approach the planning, assessment, and implementation of adaptation strategies at the regional, national, and international levels simultaneously.

In the chapter "Mitigating Climate Change in Urban Environments: Management of Water Supplies," Lawson discusses the linkage between urban water supply and climate change, including the effects of climate change on water supplies and the greenhouse gases produced by water treatment and distribution.

Lawson argues that the possibility of mitigating climate change through water supply decisions has not been fully explored. The author investigates the potential for improved efficiency through analysis of water supply systems in the five largest US cities: New York, Los Angeles, Chicago, Houston, and Philadelphia. These cities demonstrate opportunities to reduce greenhouse gas emissions from water supplies through protecting water sources, selecting alternative water supplies, repairing and replacing old infrastructure, conserving water, and using alternative energy supplies. The author also discusses the potential of decentralizing water supply system and using alternative approaches such as rainwater harvesting for improved energy efficiency in managing urban water supplies.

In the chapter “The Impact of Urban Water Use on Energy Consumption and Climate Change: A Case Study of Household Water Use in Beijing,” Chen et al. discuss the linkage between household water use and energy, and explore potential pathways for climate change mitigation. The authors argue that understanding energy consumption patterns of urban dwellers can be used in the integrated management of water and energy, amplifying the potential of energy savings by water conservation and thus reducing greenhouse gas emissions by cities. The authors report studies on energy consumption related to household water use in Beijing during summer and winter. Their study shows that household water conservation leads to significant energy savings that can be credited toward mitigating climate change effects in Beijing.

Finally, in the chapter “Reducing Carbon Footprint of Water Consumption: A Case Study of Water Conservation at a University Campus,” Parece et al. discuss the linkage between environmentally relevant behavior and water conservation that leads to reductions in energy use thereby mitigating effects of climate change. The authors report on studies conducted at an American university campus and the effects of student behavior on water use and conservation. Occupants of ten residence halls at the university were studied, and the project employed five different strategies, each with a different number of prompting strategies to determine the approach that was most effective in influencing less water use. Lower water consumption was observed in most residence halls participating in the study. In turn, energy used to treat river water to potable standards and transport it to university campus was also reduced. Ultimately, these energy savings reduce the size of the university’s carbon footprint and mitigate climate change effects.

The scientific study of climate change and technologies for adaptation and mitigation continue to evolve. The global economy, the health of people, animals, and plants, and the quality of our global environment are all affected by climate change. There is a critical and urgent need to develop climate-change-related educational programs that teach the basic science of climate change, and teach cutting-edge technologies and policies for mitigating and adapting to climate change. Regulatory aspects of climate change mitigation and adaptation at the local, regional, and global levels should also be taught. Furthermore, there is a significant need to develop appropriate local, regional, national, and international socioeconomic policies to minimize the adverse effects of climate change.

We hope this book will serve as a valuable resource and reference for graduate and undergraduate students in water and environmental sciences, and those in international studies programs, and that it will serve as a useful guide for governmental agencies and policy makers who plan and manage water and energy resources.

Blacksburg, VA, USA Tamim Younos
West Lafayette, IN, USA Caitlin A. Grady

Contents

Part III Climate Change Mitigation Strategies

Part I
Future Precipitation Projections

Projecting Future Climate Scenarios for Canada Using General Circulation Models: An Integrated Review

Mohammed H.I Dore and Peter Simcisko

Abstract This chapter provides an overview of the General Circulation Models, Regional Models, and "downscaling" techniques which can improve model resolution at the local level. Authors review the available literature on projections of precipitation over the next 100 years for Canada. The future projections of Canada as a whole are considered, followed by a more detailed survey of precipitation projections including the possibility of dry spells. The stream-flow projections for the major river basins of Canada are also considered. Finally a detailed treatment of projections by regions, such as the North, southern Ontario, southern Quebec and New Brunswick, and western Canada, is presented. Authors conclude that: (a) from the literature reviewed, it appears that changes to the Canadian climate are projected to occur under virtually all scenarios and with all models and (b) the northern and western parts of Canada may be affected most severely by climate change. There are some obvious policy implications.

Keywords Canada precipitation, Future climate scenarios, General circulation models, Statistical downscaling

Contents

M.H.I. Dore (✉) and P. Simcisko
Climate Change Lab, Department of Economics, Brock University, St Catharines, ON, Canada L2S 3A1,
e-mail: dore@brocku.ca; ps04hc@brocku.ca

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 3–28, DOI 10.1007/698_2013_220,

1 Introduction

This chapter provides an in-depth survey of the readily available body of research papers offering scenarios for possible future climate in Canada. These projections cover the period up to year 2100 and are based on projected changes in greenhouse gas concentrations and sulfate aerosol loadings using General Circulation Models and Atmosphere-Ocean General Circulation Models (AOGCM), which are complex models coupling various components of the climate system. A comparison of responses from several models can indicate the degree of uncertainty in the projections. Agreement among most model simulations allows a number of findings to be classed as "virtually certain" or "very likely." This chapter states the various climate change scenarios that have been accepted by the Intergovernmental Panel on Climate Change (IPCC). A brief guide to the work of the IPCC is presented in the Appendix.

This chapter is organized as follows. The first section explains the meanings of the General Circulation Models as well as Regional Climate Models. Because of their coarse resolution, both require some method of incorporating the effects of local topological features, which are usually carried out by some statistical methods, called "statistical downscaling." In Sect. 3, the future projections of Canada as a whole are considered. Section 4 is a more detailed survey of precipitation projections including the possibility of dry spells. This is followed, in Sect. 5, by the stream-flow projections for the major river basins of Canada. Section 6 is a detailed treatment of projections by regions, such as the North, southern Ontario, southern Quebec and New Brunswick, and western Canada. Section 7 draws some conclusions.

2 Projections of Climate Change for Canada

Climate models are used for making projections of what the future climate will look like under human influence. As with any other kind of modeling, it is necessary to establish that the model being used is an adequate representation of the underlying system, in this case the very complex climate system. Thus, firstly the present day climate is simulated without any changes in external influences (such as radiative forcing). This is often referred to as a “validation simulation,” and is usually carried out for the 1961–1990 period. It is important to assess the quality of simulations by comparing the simulated conditions to the ones that are actually observed. Once it is established that a specific model is reliable in its ability to simulate observed climate conditions, projections of future climate scenarios can be built.

There are two main approaches to making climate change projections. One is the so-called equilibrium climate simulation (or equilibrium-response experiment). The basic principle is to double the carbon dioxide concentration and then run a simulation until the model reaches a new equilibrium. This new equilibrium is then compared to the results obtained from the original (validation) simulation to get an idea of how the climate responds and is sensitive to radiative forcing. This type of simulation is time-independent in the sense that simulations are not run for specific time periods, but rather for specific blocks of time. For example, a simulation marked as “1900–2100” refers to a simulation of a 200-year period, but this could be any 200-year period. A great advantage of equilibrium climate simulations is that they are not very demanding in terms of computational power requirements, largely due to a very simplistic representation of ocean bodies in these models, or slab ocean models, in which the ocean is represented as a fixed-depth layer of water without any currents. Due to the simple representation of the ocean, however, these models reach a new equilibrium in a much shorter time frame than more complex models such as fully coupled atmosphere-ocean models.

The other approach is referred to as transient climate simulations, which are much more computationally demanding, but owing to great advancements in computing technology, have become more accessible in recent years. This approach requires that a set of predefined “scenarios” be established, where each scenario reflects some key assumptions about global population growth and the use of fossil fuels, which lead to greenhouse gas emissions. The IPCC has created several such scenarios. Originally these were called the “IS92 scenarios” [1], which were later replaced and updated in the IPCC *Special Report on Emission Scenarios* (SRES) [2]. These new SRES scenarios establish a time profile of greenhouse gas emissions and aerosol concentrations. Thus, this simulation shows how the climate would respond to potential changes in the initial conditions for real world situations.

The most commonly considered scenario in the literature is the so-called A2 scenario. One reason for it to be the most commonly considered scenario is due to the fact that models forced with the A2 scenario tend to project the greatest global warming, and as such are in a way a “worst-case” scenario. The A2 emissions scenario is characterized by continuous global population growth, and regionally focused economic growth. What follows is a brief description of the four scenario families (A1, A2, B1, and B2) as defined by the IPCC in the *Special Report on Emissions Scenarios* [2], in order to give the reader an overview of the major assumptions underlying future projections.

The A1 Storyline and scenario family can be divided into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), nonfossil energy sources (A1T), or a balance across all sources (A1B), where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.

The A2 Storyline and scenario family considers a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

The B1 Storyline and scenario family considers a convergent world with the same global population, that peaks in mid-twenty-first century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate change initiatives.

The B2 Storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The IPCC also makes note of the fact that these scenarios do not take into account climate change *mitigation* initiatives such as the United Nations Framework Convention on Climate Change, or the emissions targets set out by the Kyoto Protocol, which is due to expire at the end of 2012.

It is common practice to run simulations with an ensemble of models as opposed to using only single model on its own. This is done with the aim of reducing the systematic biases of individual models.

2.1 General Circulation Models

General Circulation Models (GCMs) are mathematical models composed of complex equations “representing physical processes in the atmosphere, ocean, cryosphere, and land surface."[1] They are used to make projections for climate change under various forcing scenarios. The most complex models from this family are referred to as Atmosphere-Ocean General Circulation Models (AOGCMs), which include the complex interactions between oceans and the atmosphere. These models have proved to be very useful in simulating the large-scale features of observed climate, and for this reason they are widely used today to make projections for future periods. GCMs are essentially the same models as are used to make weather forecasts, but they also include the effect of greenhouse gases, and divide up the earth into "grid boxes." Division into grid boxes of a fairly large size is necessary in order to ease the computational requirements of these models. Thus, GCMs are mainly used to make climate projections at the continental scale, and other methods are employed when more detailed information is required. These other methods are discussed below.

Most major developed countries have produced a GCM. In Canada, for example, the Canadian Centre for Climate Modeling and Analysis[2] has developed a coupled global climate model, CGCM, currently in its fourth version (CGCM4). The GCM developed by the UK is called HadCM, currently in the third version (HadCM3) and Germany has ECHAM, currently in its fifth version (HadCM5). Australia and Japan also have their GCMs; for more information, the reader may consult the website of the IPCC Data Distribution Centre.[3]

General Circulation Models cover a large number of climate variables. These include the following: mean temperature, maximum temperature, minimum temperature, diurnal temperature range, precipitation, snow water content, relative humidity, specific humidity, sea ice, mean sea level pressure, vapor pressure, surface temperature, incident solar radiation, wind speed, evaporation, potential evapotranspiration, soil moisture, and fractional cloud cover. In this review we concentrate mainly on precipitation.

On a global basis, the results from all models generally yield comparable results. One of their shortcomings, however, is their inability to reproduce observed climate patterns on a regional level. In fact, large discrepancies among GCMs exist with respect to regional projections. For example, Aubeeluck and Dore [3] found that the Australian GCM was in general better at projecting precipitation patterns for southern hemisphere locations whereas the Canadian GCMs were better for Canadian locations.

GCMs have limitations for regional predictions partly due to their coarse resolution which do not include topological features of landmasses, and also partly due to limitations in surface physical parametrization. For example, some parts of the Canadian Arctic Archipelago are misrepresented in GCMs, potentially causing large biases in the temperature regimes simulated by these models [4]. Like most models, GCMs provide a simplified view of the earth and its climate. The projected

[1] *Source*: IPCC website (http://www.ipcc-data.org/ddc_gcm_guide.html).

[2] Canadian Centre for Climate Modelling and Analysis: http://www.cccma.ec.gc.ca/.

[3] See http://www.mad.zmaw.de/IPCC_DDC/html/IS92A/index.html.

climate abstracts from real topological features of the earth. For example, the grid boxes representing Canada do not have the Rocky Mountains or the Great Lakes as a feature of the terrain.

Because these local features are not included in the GCMs, for realistic purposes, the projections for each grid box have to be "downscaled" using a variety of techniques, of which the simplest and the cheapest is some form of statistical approach to downscaling, to capture the real topological features located within particular grid boxes [5].

2.2 *Regional Climate Models*

Regional climate models (RCMs) offer a higher spatial resolution than GCMs. These models are "driven by atmospheric data from long coupled GCM simulations" [6]. In effect, RCMs perform dynamic downscaling of data simulated by a GCM.

For the purposes of impact and adaptation studies, information about climate change is required at a much finer spatial resolution than what GCMs are able to provide. The spatial resolution of RCMs is an improvement, but often the equivalent of station-specific data is required.

2.3 *Statistical Downscaling*

Statistical downscaling methods provide detailed site-specific data which can be crucial for climate change impact studies. Furthermore, they are computationally inexpensive. Given dissatisfaction with the existing statistical downscaling methods Dore and Burton [5] developed two downscaling models using autoregressive integrated moving average (ARIMA) methods. A detailed description of the ARIMA downscaling method can be found in Appendix A at the end of this chapter. Some other downscaling methods include the Statistical DownScaling Model [7] and the Long Ashton Research Station Weather Generator – LARS-WG [8].

Even though a great degree of agreement among models exists, there are some areas where a large variation in the projected results shows up. Models have a tendency to agree with respect to global projections; however, there is more uncertainty for regional projections. This can be partially attributed to the details of the simulated climate processes and the sensitivity of projections to spatial patterns of aerosol concentrations. For greater detail about various models, as well as uncertainties in projections, see the IPCC Third Assessment Report [9].

With the above background in mind, this chapter considers future climate projections for Canada, with the intention of identifying both areas of convergence and areas of disagreement. It is not our intention to present quantified estimates of future climate variables, as these are discussed in great detail within each respective study. The focus here is on the major directions of change and on identifying consistent patterns in projections over the vast area that Canada covers. We do, however, present a significant amount of detail for the Sooke Reservoir in British Columbia (Sect. 6.4). This is done to give the reader a better idea of how much variation among individual model projections exists for any given area.

3 Canada as a Whole

There is a great deal of evidence that climate change is already well under way, and many studies have been devoted to analyzing the changing patterns in climate variables around the globe. Dore [10] provides an extensive review of the literature pertaining to changing patterns of precipitation observed in the data across the globe. One of the main conclusions of his work is that there is increased variance in precipitation everywhere, and dry areas are getting dryer, while wet areas are getting wetter. Some further patterns that emerged from this review were increased precipitation in high latitudes (Northern Hemisphere); reductions in precipitation in China, Australia, and the Small Island States in the Pacific; and equatorial regions becoming more variable. These observed changes are said to be a "signature of global climate change."

Specifically for Canada, Vincent and Mekis [11] consider a number of temperature and precipitation indices, during two time periods namely 1950–2003 and 1900–2003. The general trends observed for both these time periods are similar. For precipitation, the observations reveal significant trends for days with precipitation as well as days with rain, that is there will be more days with precipitation, and also more days with precipitation falling as rain. Significant decreasing trends, on the other hand, were found in maximum number of consecutive dry days, as well as the simple day intensity index of precipitation and rain across Canada. The study indicates a significant increase in the number of warm events (warmer than average), and a significant decrease in the number of cold events for both studied time periods. Furthermore, over the considered time period, nighttime warming was observed to be more intense than daytime warming, resulting in a decrease of the diurnal temperature range.

The results presented above are in agreement with the results of an earlier study by Zhang et al. [12], who analyzed temperature and precipitation trends over the 1900–1998 period for southern Canada, and over the 1950–1998 period for the whole country. Their results showed that the Canadian climate has been getting warmer and wetter over the 1950–1998 period.

In the following sections, we turn our attention to actual projections of climate change. A great deal of work is done by the IPCC Working Groups who produce their own reports. Based on these reports the IPCC produces its own summary in an "IPCC Assessment Report." The most recent assessment report is the *Fourth Assessment Report* (AR4) (IPCC [13], and the Fifth Assessment Report (AR5) which is due to be completed in 2014. The assessment reports published so far cover climate change projections on a global scale, and do not include a great deal of detail at the regional level. Thus, our focus here is on projected changes in precipitation across different regions of Canada, as well as projected changes in stream-flows of various river basins in Canada. Thus, this paper brings together the findings of a number of research works with a geographical focus on Canada. It is expected that presenting these findings together in one place will make any potential patterns more obvious, and thus will contribute to our confidence in the projections. It will also be useful for comparisons with projections for other northern hemisphere countries.

4 Precipitation

Changes in precipitation patterns are key indicators of changes in climate. There are numerous variables that cover precipitation, such as mean annual rainfall and mean annual days with rainfall. Additionally, there are other measurements of precipitation that are more concerned with the frequency and intensity of extreme events. Precipitation extremes are often expressed as return periods of annual maximum events. For example, a 30-year event is said to occur with probability 1/30 in a given year on average. If the return period decreases, then a more extreme event (one with a larger amount of precipitation) is likely to happen with a greater probability; that is such an extreme event is likely to become more frequent. Extreme events can have very serious implications, and global projections point to an increased occurrence of these events. For example, precipitation events that were considered extreme in the year 2000 may be twice as likely to occur by the end of the twenty-first century under conditions of climate change scenarios [14].

The Canadian Climate Change Adaptation Project (CCAP) published a report in 2010 [15]. Within this report, projections for major Canadian cities were presented. The projections were obtained using an ensemble of 24 GCMs, put together by the Canadian Climate Change Scenarios Network (CCCSN). All GCMs were forced with the A1B emissions scenario, so as to provide "medium" projections of the future climatic conditions. Winter precipitation was projected to increase in all regions, which is especially pronounced for the Winnipeg area, further increasing the sensitivity of this region to spring flooding. Precipitation in the summer months is likely to experience only small changes in most regions of Canada, with the exception of southern British Columbia and Alberta, where a substantial decrease in precipitation is projected to occur by 2050. As noted in the report, this may have serious implications for forest fire risk within lower mainland and B.C. interior – areas which are already considered at-risk. Although not as substantial as in the case of B.C., summer drying is also projected for southern Ontario, Quebec, and Prairie regions, potentially affecting drinking water supplies, as well as hydroelectric power generation.

Sushama et al. [6] compared simulations performed with two different versions of the Canadian regional climate model (CRCM) for the IS92a and A2 scenarios.

Although the magnitude of projected changes in precipitation differs between the two versions of the CRCM, there is agreement on the direction of change. Five of the six studied river basins (Fraser, Mackenzie, Yukon, Nelson, and Churchill) were found to exhibit increases in annual precipitation. The largest increase in annual precipitation is projected to occur in the Yukon basin, while no increase is expected for the Mississippi basin. These findings are in good agreement with other studies, as the Yukon basin is located furthest North, while the Mississippi basin is located furthest south of the six studied basins.

Wang and Zhang [16] estimate changes in the risk of winter extreme precipitation over North America using statistical downscaling of a GCM forced with the SRES A2 scenario. Largest increases in the 20-year return level of daily precipitation were projected to occur in the central and southern United States and the Pacific Northwest (Oregon, Washington, Idaho, Montana, British Columbia, and Alberta). They found a lower risk of extreme precipitation in the Canadian prairies, northern Alaska, and southern Mexico, but it was pointed out that the confidence in these predictions is low.

This result for the Canadian Prairies is further reinforced by the findings of Mailhot et al. [17] who projected no decrease in the return periods of annual maximum precipitation events in this region, over the period 1850–2100. This means that extreme events are not going to occur more often than they do in today's climate. However, their findings pointed to a shift in the occurrence of these events, projecting that they will tend to occur earlier in the year (a shift from the summer months to the spring months). Seasonal shifts in precipitation patterns can have serious implications for agriculture, as less precipitation is projected to occur in the summer growing months, but also for flooding, since more springtime precipitation can translate into an increased probability of flooding due to spring ice jams.

Mailhot et al. [17] analyzed simulation results of the CGCM3. The analysis focused on the evolution of intensity and frequency of daily and multiday precipitation in a future Canadian climate. Three scenarios were considered (A1B, B1, and A2), and the most severe effects were observed under the A2 scenario, under which all of Canada saw decreases in return periods of annual maximum events, except for the Prairies as already noted above. The seasonal shift of precipitation patterns that was projected for the Prairies was also noted for most other regions of Canada. Generally projections show a decrease in the frequency of occurrence of annual maximum events in the summer months, and an increase in the spring and/or winter months. A shift away from the summer months is also projected for the northern region of Nunavut, but the shift is toward the autumn months in this case. North West Territories and the western parts of BC and Yukon were the only regions where no change in the seasonal occurrence of precipitation events was noted.

Mladjic et al. [18] carried out simulations using the Canadian Regional Climate Model (CRCM) to evaluate and assess future (2040–2071 period) changes to precipitation characteristics for the April–September period over Canada corresponding to the SRES A2 scenario. Namely, they consider the return levels of single and multiday annual maximum precipitation amounts. They utilized two techniques in their analysis: the Regional Frequency Analysis (RFA) and the Grid

Box Analysis (GBA). The largest percentage increases are projected to occur in the northern climatic regions, even though in absolute terms these are the smallest. The largest changes in absolute terms are projected to occur along the west coast. Decreases in annual maximum precipitation amounts were projected to occur mainly in the southern regions (albeit sporadically), but no clear patterns at the regional level were observed.

It is noteworthy that the CRCM tends to underestimate (negative performance errors) extreme weather events over most of Canada, the one exception being Yukon where positive performance errors are observed. The relatively short (30 year) sample size may negatively affect the statistical significance of changes to return levels for the 50- and 100-year return periods. An increase in the severity and duration of extreme precipitation events will have severe implications especially for water-related infrastructure such as combined sewer systems. These consequences of climate change were pointed out in Mladjic et al. [18] as well as in a Brock University Honors Economics Thesis by Shah, supervised by Dore [19].

4.1 Dry Spells

An alternative approach to looking at precipitation patterns is to consider the frequency and length of dry spells. These are defined as periods of a certain number of consecutive days in which precipitation does not exceed a predetermined threshold (i.e., 0.5, 1, or 2 mm)

Sushama et al. [20] studied the dry spell characteristic over Canada for two future time periods (2041–2070 and 2071–2100) and compared them to dry spell characteristics over the 1971–2000 period. They utilized simulations from the fourth generation of the Canadian Regional Climate Model (CRCM), driven by the third generation Canadian General Circulation Model (CGCM3) forced with the SRES A2 scenario. They found an increase in the mean number of dry days for southern regions in Canada, suggesting a dryer climate in these regions, but an opposite trend for the rest of Canada. Furthermore, they found a decrease in the mean number of dry spells in the southern regions, but an increase in other regions of Canada. Together this seems to imply a higher chance of droughts in the south, since fewer dry spells together with an increase in dry days indicate fewer but longer periods of dry weather throughout the year. The rest of Canada may expect to see a wetter climate on average, but also more variability in precipitation.

Schwalm et al. [21] note that the devastating drought which occurred in North America during the 2000–2004 period may actually be considered "an outlier of extreme wetness" toward the latter half of the twenty-first century, when more severe drought periods can be expected. This is a very worrying projection given that the 2000–2004 drought was the worst event in 800 years.

The results of various studies summarized in this section uncover a few distinct patterns of future changes in precipitation within Canada. It appears that most regions will see increases in the amount of precipitation throughout the year.

Most notable changes are likely to occur in the north and western regions. These regions will likely see not only an increased amount of precipitation, but also an intensification of extreme precipitation events. The southern parts of Canada and the Prairies will likely observe very little if any changes to precipitation patterns. However, there is some evidence that these regions will be more prone to droughts under future climate scenarios.

Changes in precipitation patterns can have serious and expensive implications for social infrastructure. A thorough analysis of climate change projections for a number of Canadian cities, and a quantification of its financial implications for social infrastructure was carried out by Dore and Burton [5]. The main focus was on estimating the impacts of climate change on the availability of drinking water supply and capacity for treating wastewater, and also the impact on road networks. In their analysis, the CGCM1 model was utilized, forced with the GG emissions scenario (the GG scenario is an older scenario which was used before the Special Report on Emissions Scenarios was published in 2000). The outputs from the CGCM1 were downscaled using the so-called *proportional downscaling* method. It was found that precipitation will likely increase in higher latitudes, especially in the winter months. The Great Lakes may experience a lowering of water supplies and lake levels, even though precipitation is projected to increase in the Toronto area. The changes for Toronto include a notable increase in maximum precipitation (by a factor of 4 compared to the baseline period of 1961–1990) and an increase in the variability of precipitation (an increase in the standard deviation by a factor of 1.7 compared to the baseline period). The analysis showed a wet autumn in the Niagara region, followed by a wetter winter. A dramatic increase in maximum precipitation is projected to occur in the Halifax area, especially from the baseline period to the 2010–2039 time period.

5 Stream-Flow

Projections of future stream-flows are important for various sectors of the economy, such as agriculture and hydroelectric power. Stream-flow data are also important for ensuring that existing infrastructure is adequate for dealing with changes in flow rates, as there will be a need for planning for flood events in the future.

Seasonal flooding of the Chateauguay River Basin in southern Quebec under future climate scenarios was evaluated by Roy et al. [22]. Using a coupled hydrology–hydraulics model of the basin in conjunction with results from the CGCM1, the authors consider potential future changes in the volume of runoff, maximum discharge, and water level. It was found that for the summer and fall periods, discharge levels will likely increase in the future (2020–2040 and 2080–2100). The summer and fall discharges are projected to surpass the current maximum flows observed during the spring snowmelt period. Since the spring maximum flows are already associated with flooding, an exceedance of these levels will likely result in more flooding in the future.

Quilbe et al. [23] carried out projections for the Chaudiere River in Quebec using three GCM models: (a) CGCM3, with scenarios A2 and B1, (b) HadCM3 with A2 and B2, and (c) ECHAM4 with A2 and B2. All models pointed to a small decrease in annual runoff over the projection period 2010–2039. Monthly projections were found to exhibit more variance among models, but generally increased winter discharge and decreased summer and fall discharge are projected for the 2010–2039 period. Furthermore, slight decreases in spring peak flows along with unchanged summer base flow are projected by statistical downscaling methods.

Choi et al. [24] investigated potential changes to stream-flows in river basins in central parts of Canada (Northern Manitoba, in the Taylor, and Burntwood River basins). Their study used two GCMs which fed into a hydrological model to assess potential impacts of climate change for the 2041–2070 and 2071–2099 periods under the SRES A2 and B2 scenarios. Regardless of the emission scenario, the projections pointed to increases in mean annual runoff, as well as high and low flow quintiles, for all GCMs. The number of days with extreme low flows is consistently projected to decrease by all simulations. It is noted, however, that the projections for autumn and summer runoff tend to vary greatly for different scenarios.

Shepherd et al. [25] discuss the impact of climate change on river flows of Rocky Mountain Rivers. They consider both empirical trend projections and hydroclimatic modeling. The use of this “composite analysis” allows greater confidence in the projected results. What emerged from their analysis is a considerable decline in summer flows and a modest increase in winter flows, resulting in an overall reduction in annual flows.

Poitras et al. [26] investigated projected changes in average and extreme stream-flows of ten river basins across western Canada, namely the Nelson, Churchill, North Saskatchewan, South Saskatchewan, Peace, Athabasca, Mackenzie, Yukon, Fraser, and Columbia basins. The stream-flows were derived from climate simulations performed with the fourth generation of the CRCM forced with the A2 emission scenario. Stream-flows are projected to increase in all basins, with the largest (26%) increase occurring in the most northerly basin (Yukon), and the smallest (6%) increase occurring in the Columbia basin, which is furthest south out of the ten basins. An increase in 10-year return levels of high flows is projected, especially for the basins further north, while some of the southern basins (Columbia for example) are projected to experience a decrease.

6 Regional Focus

Canada is divided into ten distinct eco-climatic provinces which are further sub-divided into eco-climatic regions [27]. It would be useful to have projections for each of these regions. However, it appears that research has been mostly carried out in a somewhat sporadic manner. The research papers which we examined for this review mostly focus on specific watersheds, river basins, or geographic regions. In this section some findings for key regions of interest are presented. Most notably the northern region of Canada, which is geographically a very complex and heterogeneous region, as well as a few other areas have received attention in the regional-level research.

6.1 Northern Regions

Northern regions of Canada are complex to model owing to heterogeneous surface conditions and the large presence of sea ice, which greatly modifies "the exchange of heat, water, and momentum between the air and the underlying surface, affecting mostly the characteristics of the local and regional climate states" [4]. Using statistical downscaling and input data from two GCMs (forced with the A2 and B2 scenarios), Gachon and Dibike [4] considered temperature change signals for the 2070–2099 period. They found a consistently lower warming in the summer months than in the other months, as well as a lower warming with the B2 than the A2 scenario (for example, in the winter months, the temperature increase as projected using the A2 scenario is in the range of 4–7°C compared with a projected warming of 3–4.5°C with the B2 scenario). The main goal of their paper was to compare the predictions of the statistical downscaling model to raw-GCM outputs, and as such it is important to note that "all downscaled results gave a higher convergence and physically plausible temperature change signal in comparison with the raw-GCM anomalies." See also Dibike et al. [28] for an uncertainty analysis of statistically downscaled climate regimes (precipitation and temperature) in the Canadian north.

Extensive work focusing on northern regions of Canada has been carried out by Prowse et al. [29–31]. Their studies provide a comprehensive review of outputs from seven AOGCMs and six emission scenarios for three 30-year periods between 2010 and 2100. They found that significant variability among model predictions exists, both for temperature as well as precipitation, and variability is even more pronounced with the latter. However, there appears to be an agreement among all models of an increasing trend of both air temperature and, for the most part, precipitation, with larger percentage increases in the northern regions of the Canadian Arctic. The authors specifically noted a "general poleward gradient of temperature increase, which will likely lead to a more uniform, future temperature climate over northern land areas" [29]. Certain seasonal patterns also emerge from their study. Largest increases in temperature are projected for the winter and fall seasons, while precipitation is projected to increase the most in winter. It is important to note that projections of future precipitation are more uncertain than temperature. Significant variability among models exists, and even though the median projections show an increase in precipitation over the Canadian North, some actually predict a decline. This is in line with the findings of other investigations, which seem consistently to point to a more pronounced warming in the North, and in the winter months (see for example, Plummer [32]).

One must be cautious when interpreting climate change projections for northern Canada because of the geographical complexity of this region. This is especially true when the projections under consideration are outputs from a GCM model, which tend to have limitations for a number of reasons, as already noted above. Furthermore, Plummer [32] noted large differences in projected winter precipitation over the Canadian Archipelago between the CGCM and CRCM. These differences are largely due to the different representations of the distribution of land and sea throughout this region. Furthermore, a lack of high-quality observational records of the past for the northern regions of Canada makes model validation difficult.

6.2 Southern Ontario

Grillakis et al. [33] consider projections from a number of hydrologic models for the Spencer Creek watershed in southern Ontario. The authors assessed potential hydrologic impacts of climate change for the watershed by imposing changes in precipitation and temperature derived from the North American Regional Climate Change Assessment Program. All models were forced with the SRES A2 scenario, and climate was simulated for the 2050–2068 period, using an equally long past period (1990–2008) for comparison purposes. Despite the variability among projections from different models, they find that “all simulations show an increase in the average inter-annual discharge, but also a noteworthy change in the seasonal distribution of the discharges” [33].

The change in seasonal distribution of discharges can be attributed to the nonuniform increases in temperature and precipitation throughout the year. In certain months, the projected increase in flows can be attributed to increased precipitation (January for example). In other months, the origin of increased flows is more complex, and can occur even where precipitation is not projected to increase. For example, no increases in precipitation were projected for the month of February, but increased discharges were projected nevertheless. In this case, the change in discharges can be attributed to the higher temperatures projected for this month, resulting in more snowmelt which occurs earlier compared to past climate. Overall, flow rates are projected to increase in winter and autumn, with the largest increases projected to occur in the months of January and February. This result confirms the findings of Dore and Burton [5] whose analysis of projections for the Niagara region in Southern Ontario showed a wet autumn, followed by a wetter winter in future periods (as described in “Precipitation”).

6.3 Southern Quebec and New Brunswick

An analysis of extreme precipitation events under the influence of climate change in the southern Quebec area was performed by Mailhot et al. [34]. By examining intensity–duration–frequency curves, they show what precipitation patterns may look like under a future (2041–2070) climate in the studied area. Annual maximum amounts of precipitation for the May–October period were considered. Projections were made using the CGCM2 forced with the A2 emissions scenario. Although the uncertainty in projections increases at larger return periods and durations, certain expected increases are noted at the 90% confidence level. Namely, the 2-h rainfall amounts for May–October annual maximum of return periods between 2 and 25 years as well as 24-h rainfall for May–October annual maximum of 2- and 5-year return periods are expected to increase. Furthermore, the return periods of 2- and 6-h precipitation events which were considered to be annual maxima in the period 1961–1990 are projected to be approximately halved in the future (2041–2070). This means that extreme precipitation events will intensify under a future climate, and events that were considered to be extreme in the past will occur more often in the future.

Groleau et al. [35] performed a trend analysis of winter (January–February) rainfall over the regions of southern Quebec and New Brunswick. The analysis is carried out using data from 60 weather stations located in the studied regions. They found an increased probability of occurrence of winter rainfall, with clearer trends emerging in the south. As noted by the authors, increased winter rainfall can have significant implications for potential flooding, especially in the presence of extensive snow cover.

Boyer et al. [36] studied potential hydrological impacts of climate change on five St. Lawrence tributaries. Their study utilized the HSAMI hydrological model developed by Hydro Quebec, which was run with climate projections generated by three GCMs under the A2 and B2 scenarios. The focus was placed on the winter and spring seasons. An increase in winter discharges and a decrease in spring discharges relative to the reference period (1961–1990) were projected to occur by most simulations. Another trend apparent from the analysis was an earlier "center-volume date" in future climate regimes. The center-volume date is the date by which half of the annual flow volume has passed through a river. Thus, an earlier center-volume date indicates that the first half of the year could become wetter. Warmer temperatures and a reduction in the snow to precipitation ratio were cited as the main contributors to hydrological changes. The results of this study are similar to the results found by Grillakis et al. [33] (presented above), which makes sense given the geographic proximity of the studied areas.

6.4 Western Canada and the Rocky Mountains

A number of studies have focused on the impact of climate change on water resources in British Columbia. A review of these studies was presented by Merritt et al. [37]. Besides providing a review of several studies, Meritt et al. also carried out simulations for the Okanagan Basin. Using three GCMs and the University of British Columbia Watershed Model, projections corresponding to the SRES

A2 and B2 scenarios were carried out for a number of subwatersheds within the basin. All three models utilized for making projections indicate earlier onset of the spring “freshet” – the spring snow thaw. This is consistent with the findings of other studies (as per the summarized results in Merritt et al. [37]), which also found an earlier occurrence of the freshet, and a shift of the spring peak flows to earlier in the year [38–40]. Furthermore, all models agree on a “more rainfall dominated hydrograph” and reduced flow volumes in a future climate. As indicated by the authors, their results were consistent with other studies for this geographical area.

Larson et al. [41] use climate change scenarios to estimate spring stream-flow within the St. Mary Watershed for the 1961–2099 period. Although this watershed is not fully situated in Canada, as part of it is across the border in the United States, it is of importance to agriculture in Southern Alberta, where it provides “almost 200,000 ha of downstream irrigation” [41, p. 37]. Substantial warming is predicted under both scenarios (A1 and B1), but only a modest increase in winter and spring precipitation is projected. However, an increase in the rain to snow ratio and higher snowmelt frequency in winter (due to warming) in future periods are identified as contributing factors to reduced spring stream-flow. The authors point to significant implications for water storage facilities in the projected future, with potentially severe water shortages occurring during drought years.

Changing patterns of precipitation at the Sooke reservoir in B.C. were investigated by Dore et al. [42]. Using statistical techniques, they analyzed daily precipitation data covering the period 1914–2004, in an effort to identify possible signals of climate change. Their analysis showed a change in at least three of the moments of the distribution of precipitation. Most notably, a change in the variance of precipitation was identified, prompting the Victoria local authorities to take action by expanding the capacity of the reservoir at a cost of significant capital investment of $23 million [42].

Considering the signals of climate change observed in existing data, Dore [43] did extensive work on future projections for the Sooke Reservoir located in British Columbia. Using statistical downscaling methods (outlined in the Appendix), projections from four GCMs were downscaled to obtain projections of daily and monthly precipitation for this reservoir. The four GCMs consisted of two Canadian models (CGCM2 and CGCM3), the U.S. developed NCAR[4] model, and the U.K. HadCM3[5] model. Below is a summary of the results for both daily precipitation and extreme projections quoted directly from their study. The results for the Sooke Reservoir are presented in detail in order to give the reader a glimpse at how projections differ depending on the model used. The differences are many, but nevertheless there still are patterns that emerge. These patterns are presented after the detailed summary of results for projections of the Sooke Reservoir.

---

[4] For information on the NCAR model see http://ncar.ucar.edu/community-resources/models.

[5] For information on the HadCM3 model see http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadcm3.

6.4.1 Daily Projections

1. Future precipitation projections were downscaled from the Canadian general circulation models, CGCM2 and CGCM3. These projections show that annual precipitation is expected to increase by up to 12% over the next 100 years.
2. Precipitation could decline for the 2020s time slice according to results from Runs 1 and 2 of the CGCM3 model. However, this decline is very small (approximately 1%).
3. The CGCM2 projections over the next 100 years suggest that precipitation levels would increase by about 8% for the next 30 years (2011–2040), continue along this pattern for another 30 years (2041–2070), and increase by 12% for another 30 years (2071–2100).
4. For the NCAR model, annual precipitation for the next 100 years is expected to increase between 13% and 17%.
5. The NCAR model projects a 17% increase during the period 2010–2039s, the highest of all GCM projections for the period while HADCM3 model projects an 18% increase for the 2070–2099 time slice (also the highest increase of all GCMs for that time slice).
6. There seems to be a consistent indication for the 2070–2099 time slice that annual precipitation is projected to increase between 10% and 13% for the NCAR model while the HADCM model predicts an increase of about 18% for the same time period.
7. When the daily projections were converted to monthly projections, it was found that the CGCM2, NCAR, and HADCM3 models show an increase (both in percentage and absolute terms) in precipitation for historically "wetter" and a decrease in precipitation for the historically drier months.
8. January, February, March, September, October, and November all showed increases (absolute and percentage) while for historically "drier" months May, June, and July precipitation is projected to decrease (for CGCM2, NCAR, and HADCM3).
9. For all runs in the CGCM3 model, they found that in general precipitation is projected to decline during the first 5 months of the year while latter 5 months of the year was projected to have an increase in precipitation.
10. The CGCM3 model projects an increase in precipitation for (the "drier") May and June but an increase for July and August contrary to the CGCM2, NCAR, and HADCM3 projections.
11. Both the CGCM2 and CGCM3 models predict a large increase in precipitation for September, October, and November.
12. The NCAR and HADCM3 models project a larger percentage and absolute decrease in precipitation during the summer months than the CGCM models. However, the HADCM3 model predicts an even greater degree of precipitation decline for the summer months than the NCAR for the 2070–2099s time period.

13. The NCAR model projects a higher percentage increase in precipitation than the CGCM models for the months of January, February, and March for all time slices.
14. On the other hand, the NCAR model projects a greater degree of precipitation decline than the CGCM model between the months of June–September.
15. The CGCM2 model has similar trends in percentage differences as the NCAR model has unlike the CGCM3 model; in general precipitation is expected to increase (in percentage terms) in the first third of the year, decline during the spring and summer months, and increase during the winter months for the CGCM2.
16. The CGCM2 model shows a percentage increase in precipitation beginning in August while NCAR and HADCM3 show an increase from October onward (for all time periods).
17. For all runs in the CGCM3 model an increase in precipitation (in percent) is expected between the months of July–October during all time periods.
18. The CGCM3 model projects a relatively low percentage decline in precipitation for the first 6 months of the year for all time periods.
19. Compared to all other models, the NCAR and HADCM3 models project the largest percentage decline in precipitation for the summer and other months with historically low precipitation.
20. All models project large increases in absolute precipitation during the latter months of the year while NCAR and HADCM3 also show large increases in absolute precipitation during the earlier months of the year.
21. As expected, absolute changes in precipitation for all three runs of the CGCM3 show similar patterns. The CGCM3 model shows the largest absolute increase in precipitation for the month of October during the 2041–2070 time period.
22. The NCAR model shows the largest absolute increase in precipitation for November (during the 2050s) while the HADCM3 model shows the largest absolute increase for December (during the 2080s).
23. HADCM3 shows the largest absolute increases in precipitation for the first 3 months during the 2080s while NCAR shows this during the other two time slices.

6.4.2 Extreme Projections

1. February and November are projected to have the largest absolute decline in monthly (extreme) low totals followed by March and December for the CGCM2 model.
2. For all GCMs, during the 2010–2040 period, there is a greater difference between the observed monthly totals and the projected extreme low monthly totals for the first 3 and last 2 months of the year than for the other months of the year.
3. Since the summer months contained very low (some close to zero precipitation) many models were not able to capture this feature in the projections.

The NCAR and HADCM3 models were the only two models which were able to produce zero precipitation totals during the summer months.

4. Nevertheless, CGCM2 and CGCM3 both produced very low totals (between 1 and 5 mm per month as an extreme low projection).
5. For all models, the months of February and November are generally expected to have the largest millimeter decline in total precipitation for an extreme low precipitation scenario.
6. The CGCM2 generally predicts a lower extreme precipitation than the CGCM3 model on average for the 2071–2100 time period.
7. Both the HADCM3 and NCAR project an extreme low of zero precipitation during September for the 2070–2099 period.
8. For the extreme maximum projections, the CGCM models generally project higher extreme maximum precipitation during the latter months of the year while the NCAR predicts higher extreme precipitation during the earlier months.
9. For extreme maximum projections, a greater millimeter increase in precipitation in an extreme scenario during the wetter months than during the summer months is expected.
10. For the 2010–2039 period, the NCAR model projects the highest maximum extreme precipitation for January, March, and April while the CGCM3 Run 3 predicts the highest maximum extreme for February and May. The CGCM3 Run 2 projects the maximum extreme precipitation for June and August while CGCM Run 1 projects the maximum extreme precipitation for July, September, and October. The CGCM2 model projects the maximum extreme for November and December.
11. For the 2011–2040 period, the summer months can expect between 5 and 60 mm above the observed maximum while autumn and winter months can expect between 40 and 140 mm of precipitation above the observed maximum. Spring months can expect between 10 and 110 mm above the observed maximum.
12. For the 2040–2069 period, the NCAR model projects the highest extreme precipitation for March and April. CGCM3 Run 1 projects the highest extreme for January alone while CGCM3 Run 2 projects the highest extreme for July, September, November, and December. CGCM3 Run 3 projects the highest extreme precipitation for June and October. CGCM2 projects the highest maximum extreme for February, May, and August.
13. For the 2040–2069 period, the summer months can expect between 5 and 90 mm above the observed maximum while autumn and winter months can expect between 40 and 160 mm of precipitation above the observed maximum. Spring months can expect between 5 and 150 mm above the observed maximum with the highest extreme precipitation projected for March (for spring).
14. For the 2070–2099 period, the NCAR model projects the highest extreme for January while the HADCM3 model projects the highest extreme for February, March, April, November, and December. The CGCM3 Run 1 projects the highest extreme for May and July while CGCM3 Run 2 projects the highest

extreme for June and September. CGCM3 Run 3 projects the highest precipitation for August and October.

15. For the 2070–2099 period, the summer months can expect between 0 and 150 mm above the observed maximum while autumn and winter months can expect between 25 and 230 mm of precipitation above the observed maximum. Spring months can expect between 5 and 150 mm above the observed maximum with the highest extreme precipitation projected for March (for spring).

For the most part, the models agree on the direction of change of future precipitation. An exception to this consistency among models is observed for the annual precipitation projection for the 2020s time period. Runs 1 and 2 of the CGCM3 model predict a possible decline in annual precipitation, contrary to what all the other models predict. Nevertheless, the projected decline is rather small, in the order of 1%. Although differences in the magnitude of projected changes among models exist, all models consistently point to a pattern of historically drier months receiving less precipitation in the future, while historically wetter months are projected to see increases in precipitation. Specific patterns can also be observed for precipitation extremes. Generally speaking, regardless of the model used the months of February and November are projected to see the largest absolute decreases in total monthly precipitation for an extreme low precipitation scenario. Wetter months are projected to experience a larger absolute increase in precipitation in an extreme event as compared to the summer months.

Clearly, although projections of future climate change are highly uncertain, and exhibit a lot of variation between different models, when everything is considered together common patterns emerge. In this chapter, we have presented a number of studies which use a variety of models in their analyses. In this way, it may be easier to notice common patterns of climate change projections. As we summarize the results in the following section, it becomes clear that climate change in one form or another is projected to occur in all regions of Canada.

7 Conclusions

From the literature reviewed above, it is obvious that changes to the Canadian climate are projected to occur under virtually all scenarios and with all models. Although regional differences exist, with some areas being affected more severely or in different ways than others, changes are projected to occur everywhere. Thus, it is important for policymakers to take this into account, and develop adequate policies for adapting to climate change; adaptation usually means improving all infrastructures to make it more resilient to the impacts of extreme climate events, from extreme precipitation to extreme heat waves.

The implications of climate change may be very different for various regions of Canada. As is evident from the projections currently available, the northern and western parts of Canada may be affected most severely by climate change. In light of the regional differences that persist, it may be useful to develop a comprehensive study which will consider climate change projections for each of the eco-climatic regions of Canada. This would allow one to get the full picture of how Canada's diverse regions may be affected by future climate scenarios.

Climate change is a reality that has been taking place for a number of years, and is projected to continue into the future under many potential scenarios. Thus, much effort should be exerted on the part of policymakers to develop mitigation and adaptation strategies. Mitigation means reducing the emissions of greenhouse gases, possibly by international cooperation through binding treaties, such as the Kyoto Protocol. For adaptation, it means, for example, strengthening of building codes to reflect the future climate's impact on infrastructure. Comprehensive mitigation strategies at the national level need to be enhanced, especially as the future of the Kyoto Protocol remains uncertain. For example, Canada should implement mitigation policies that are consistent with Western Europe, which seems to making rapid progress not only in adaptation but also by pursuing serious mitigation policies to reduce the use of fossil fuels.

Acknowledgments Funding for this research is provided by the Social Sciences and Humanities Research Council of Canada. However, the views expressed here are the responsibility of the authors alone.

Appendix A: Description of Dore's ARIMA Downscaling Method

Details of how downscaled projections are obtained using Dore's ARIMA method are described below. These steps are also presented in a thesis by Ashwina Aubeeluck (2006) supervised by Dore [3].

Step 1

We fit the best ARIMA model to the base years (1961–1990) of the respective GCM models. The fitted values obtained for the base years can be denoted as Arima(m, y) where m is the month and y is the year. We also divide each GCM models into three time slices, the 2020s, 2050s, and 2080s, from which one time slice is considered at a time.

Step 2

Find the mean of each month over the 30-year period for the fitted values, Arima (m, y). For example, mean of January can be calculated as follows:

$$\text{mean}_1 = \frac{\text{Arima}_{1,1961} + \text{Arima}_{1,1962} + \cdots + \text{Arima}_{1,1990}}{30 \text{ years}}$$

The same procedure is carried out to calculate the mean for the other 11 months.

Step 3

Divide the mean of the fitted values, mean_m obtained in step 2 by the 2020s GCM values to obtain the multipliers. We also find the maximum, $\text{max}_\text{arima}\text{mul}_m$, and minimum, $\text{min}_\text{arima}\text{mul}_m$, multipliers for each month.

Step 4

Multiply the maximum multiplier by the observed base, $\text{obs}_{m,y}$, to obtain the High Downscaled values and the minimum multiplier by the observed base to obtain the Low Downscaled values.

$$\text{High Downscaled values} = (\text{max}_\text{arima}\text{mul}_m) \times \text{obs}_{m,y}$$

$$\text{Low Downscaled values} = (\text{min}_\text{arima}\text{mul}_m) \times \text{obs}_{m,y}$$

The High and Low Downscaled values are plotted. We can also extend our analysis by finding the average of the High and Low Downscaled values. We then repeat the same steps to obtain 2050s and 2080s Downscaled values.

Appendix B: Guide to the IPCC Literature

The contents of this appendix have been taken from the IPCC website, and are presented here to give the interested reader a brief overview of the IPCC and its work. It is recommended that the reader should consult the IPCC website for further information.

Background

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established by the United

Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socioeconomic impacts. In the same year, the UN General Assembly endorsed the action by WMO and UNEP in jointly establishing the IPCC.

Activities

One of the main IPCC activities is the preparation of comprehensive assessment reports about the state of scientific, technical and socioeconomic knowledge on climate change, its causes, potential impacts, and response strategies. Four assessment reports have been prepared by the IPCC since 1988. There is a Fifth Assessment (AR5) due to be finalized in 2014. Compared with previous reports, the AR5 will put greater emphasis on assessing the socioeconomic aspects of climate change and implications for sustainable development, risk management, and the framing of a response through both adaptation and mitigation.

In addition to these comprehensive assessment reports, the IPCC also publishes special reports from time to time (such as the Special Report on Renewable Energy Sources and Climate Change Mitigation and Special Report on "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation"). Furthermore, the IPCC helps coordinate the development of new scenarios. The IPCC recommends the use of these scenarios for climate projections to allow international comparison among projections. In the past, the IPCC coordinated the development of new scenarios for its assessment reports directly, and one of the results of this work was the Special Report on Emissions Scenarios (SRES) published in 2000 (these superseded the older IS92 scenarios). The scenarios defined in the SRES (such as scenarios A1, A2, and so on as described in the main chapter) are often mentioned in the climate projections literature because these scenarios are a vital part of transient climate change simulations. However, in 2006 the IPCC decided to leave future scenario development to the scientific community. A presentation on the new process underway for developing new scenarios was provided at the 35th Session of the IPCC in June 2012.

References

1. Leggett J, Pepper WJ, Swart RJ (1992) Emissions scenarios for IPCC: an update. In: Houghton JT, Callander BA, Varney SK (eds) Climate change 1992. The supplementary report to the IPCC scientific assessment. Cambridge University Press, Cambridge, pp 69–95
2. Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Raihi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) Special report on emissions scenarios. A special report of

working group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, 599 pp. Available online at: http://www.grida.no/climate/ipcc/emission/index.htm. Retrieved 17 Aug 2012)
3. Aubeeluck DA, Dore MHI (2006) Climate change and precipitation patterns in an small island state: the case of Mauritius. Brock University unpublished paper, based on an Honours thesis by D.A. Aubeeluck
4. Gachon P, Dibike Y (2007) Temperature change signals in northern Canada: convergence of statistical downscaling results using two driving GCMs. Int J Climatol 27:1623–1641
5. Dore MHI, Burton I (2001) The cost of adaptation to climate change in Canada: a stratified estimate by sectors and regions. Social Infrastructure. Available at: http://www.spartan.ac.brocku.ca/~dore. Retrieved April 16, 2013
6. Sushama L, Laprise R, Caya D, Frigon A, Slivitzky M (2006) Canadian RCM projected climate-change signal and its sensitivity to model errors. Int J Climatol 26:2141–2159
7. Wilby R, Dawson C, Barrow E (2002) SDSM – a decision support tool for the assessment of regional climate change impacts. Environ Model Software 17:147–159
8. Semenov M, Barrow E (1997) Use of a stochastic weather generator in the development of climate change scenarios. Clim Change 35:397–414
9. IPCC TAR (2001) In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Climate change 2001: the scientific basis, contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge. Available from: http://www.grida.no/publications/other/ipcc%5Ftar/?src=/climate/ipcc_tar/wg1/index.htm. Retrieved 17 Aug 2012
10. Dore MHI (2005) Climate change and changes in global precipitation patterns: what do we know? Environ Int 31:1167–1181
11. Vincent LA, Mekis E (2006) Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. Atmosphere-Ocean 44:177–193
12. Zhang XB, Vincent LA, Hogg WD, Niitsoo A (2000) Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38:395–429
13. IPCC (2007) In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
14. Kharin VV, Zwiers FW (2005) Estimating extremes in transient climate change simulations. J Clim 18:1156–1173
15. Climate Change Adaptation Project – CCAP (2010) Climate change adaptation: a priorities plan for Canada. Available online from: http://www.adaptnowcanada.ca/report/. Retrieved April 16, 2013
16. Wang J, Zhang X (2008) Downscaling and projection of winter extreme daily precipitation over North America. J Clim 21:923–937
17. Mailhot A, Kingumbi A, Talbot G, Poulin A (2010) Future changes in intensity and seasonal pattern of occurrence of daily and multi-day annual maximum precipitation over Canada. J Hydrol 388:173–185
18. Mladjic B, Sushama L, Khaliq MN, Laprise R, Caya D, Roy R (2011) Canadian RCM projected changes to extreme precipitation characteristics over Canada. J Clim 24:2565–2584
19. Shah N, Dore MHI (2004) Combined sewer overflows in the Niagara region. Brock University unpublished paper, based on an Honours thesis by N. Shah
20. Sushama L, Khaliq N, Laprise R (2010) Dry spell characteristics over Canada in a changing climate as simulated by the Canadian RCM. Global Planet Change 74:1–14
21. Schwalm CR, Williams CA, Schaefer K, Baldocchi D, Black TA, Goldstein AH, Law BE, Oechel WC, Paw UKT, Scott RL (2012) Reduction in carbon uptake during turn of the century drought in western North America. Nat Geosci 5:551–556
22. Roy L, Leconte R, Brissette FP, Marche C (2001) The impact of climate change on seasonal floods of a southern Quebec River Basin. Hydrol Process 15:3167–3179
23. Quilbe R, Rousseau AN, Moquet J, Trinh NB, Dibike Y, Gachon P, Chaumont D (2008) Assessing the effect of climate change on river flow using general circulation models and

hydrological modelling – application to the Chaudiere River, Quebec, Canada. Can Water Resources J 33:73–93
24. Choi W, Rasmussen PF, Moore AR, Kim SJ (2009) Simulating streamflow response to climate scenarios in central Canada using a simple statistical downscaling method. Clim Res 40:89–102
25. Shepherd A, Gill KM, Rood SB (2010) Climate change and future flows of Rocky Mountain rivers: converging forecasts from empirical trend projection and down-scaled global circulation modelling. Hydrol Process 24:3864–3877
26. Poitras V, Sushama L, Seglenieks F, Khaliq MN, Soulis E (2011) Projected changes to streamflow characteristics over western Canada as simulated by the Canadian RCM. J Hydrometeorol 12:1395–1413
27. Ecoregions Working Group (1989) Ecoclimatic regions of Canada, first approximation. Ecological land classification series, no. 23. Sustainable Development Branch, Conservation and Protection, Environment Canada, Ottawa, Ont. Report with map at 1:7.5 million scale, 199 pp
28. Dibike YB, Gachon P, St-Hilaire A, Ouarda TBMJ, Nguyen VT (2008) Uncertainty analysis of statistically downscaled temperature and precipitation regimes in Northern Canada. Theor Appl Climatol 91:149–170
29. Prowse TD, Furgal C, Bonsai BR, Edwards TWD (2009) Climatic conditions in Northern Canada: past and future. Ambio 38:257–265
30. Prowse TD, Furgal C, Bonsal BR, Peters DL (2009) Climate impacts on northern Canada: regional background. Ambio 38:248–256
31. Prowse TD, Furgal C, Melling H, Smith SL (2009) Implications of climate change for northern Canada: the physical environment. Ambio 38:266–271
32. Plummer DA, Caya D, Frigon A, Cote H, Giguere M, Paquin D, Biner S, Harvey R, de Elia R (2006) Climate and climate change over North America as simulated by the Canadian RCM. J Clim 19:3112–3132
33. Grillakis MG, Koutroulis AG, Tsanis IK (2011) Climate change impact on the hydrology of Spencer Creek watershed in Southern Ontario, Canada. J Hydrol 409:1–19
34. Mailhot A, Duchesne S, Caya D, Talbot G (2007) Assessment of future change in intensity-duration-frequency (IDF) curves for southern Quebec using the Canadian regional climate model (CRCM). J Hydrol 347:197–210
35. Groleau A, Mailhot A, Talbot G (2007) Trend analysis of winter rainfall over Southern Quebec and New Brunswick (Canada). Atmosphere-Ocean 45:153–162
36. Boyer C, Chaumont D, Chartier I, Roy AG (2010) Impact of climate change on the hydrology of St. Lawrence tributaries. J Hydrol 384:65–83
37. Merritt WS, Alila Y, Barton M, Taylor B, Cohen S, Neilsen D (2006) Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. J Hydrol 326:79–108
38. Morrison J, Quick MC, Foreman MGG (2002) Climate change in the Fraser River watershed: flow and temperature projections. J Hydrol 263:230–244
39. Cohen S, Kulkarni T (eds) (2001) Water management and climate change in the Okanagan Basin. Final report, Climate change action fund project A206, 75 pp
40. Whitfield PH, Reynolds CJ, Cannon A (2002) Modelling streamflow in present and future climates: example from the Georgia basin. British Columbia. Can Water Resources J 27:427–456
41. Larson RP, Byrne JM, Johnson DL, Kienzle SW, Letts MG (2011) Modelling climate change impacts on spring runoff for the rocky mountains of Montana and Alberta II: runoff change projections using future scenarios. Can Water Resources J 36:35–51
42. Dore MHI, Matilla-García M, Marín MR (2013) Changing patterns of precipitation at Sooke reservoir in British Columbia, Canada: a parametric and nonparametric statistical analysis. Atlantic Econ J (in press DOI 10.1007/s11293-012-9346-y)
43. Dore MHI (2011) Report on daily precipitation projections for the Sooke reservoir. Brock University unpublished paper

Evaluation and Comparison of Satellite and GCM Rainfall Estimates for the Mara River Basin, Kenya/Tanzania

Shimelis Behailu Dessu and Assefa M. Melesse

Abstract Water resources and climate change studies in data-scarce regions of the world are increasingly employing satellite rainfall estimates (RFEs) and rainfall outputs from general circulations models (GCMs). The reliability of these data sources is seldom verified with observed data prior to application. This chapter outlines the application of simple evaluation techniques to assess the potential of RFE and GCMs outputs as a potential rainfall information sources in the Mara River basin (MRB), Kenya/Tanzania. Results of the assessment show that proper care is required in comparing/mixing of results from studies using different RFE in the MRB. In general, RFE and GCMs are promising sources of information, but refining the estimates with a much improved algorithms is essential.

Keywords Climate change, GCM, Mara River, RFE, Satellite rainfall, Water resources

Contents

S.B. Dessu (✉) and A.M. Melesse
Department of Earth and Environment, Florida International University, Miami, FL, USA
e-mail: sdess001@fiu.edu

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 29–46, DOI 10.1007/698_2013_219,

1 Introduction

Water resources planning and management is inevitably the foundation of sustainable development plan. Limitation of observed data stands out among the wide spectrum and variety of challenges in water resources development and management facing the developing regions of the world. The feasible threshold towards which water utilization could be pushed is crucial information to ensure sustainable development. In these regions, water resources data and information are either absent or limited in time and location. With the advent and progress of remote data collection and development of complex earth system models, satellite rainfall estimates (RFEs) and rainfall outputs from general circulations models (GCMs) are becoming readily available for end-users offsetting the limitations posed by data scarcity. A number of algorithms and mathematical approaches have been developed to model rainfall process with varying complexity in representations of the natural process, theoretical concepts and assumptions, temporal and spatial scale, computational efficiency, data requirement, etc. Their application ranges from simple daily rainfall estimation/forecast to simulation of complex hydrologic processes that supplement decision.

The use of satellite RFE requires proper verification as the remote sensing approaches usually combine different factors that determine the information sought for. Remote sensing information also depends on number of variables considered in the measurement and estimation process. For example, precipitation is highly influenced by topography and concentration of aerosols at a particular time and prediction of precipitation from cloud temperature may not provide complete picture of rainfall event. The daily RFE distributed by USAID and Famine Early Warning Systems Network (FEWS NET) (http://www.fews.net) program is one of the widely used satellite estimate in Africa and other developing regions of the world. We have used this estimate to explore easy-to-use techniques in evaluation of the performance of similar estimates in water resources assessment.

GCMs are increasingly used to simulate past and future climate scenarios [1]. GCMs outputs have become part and parcel of hydrological systems study due to the fact that water resources planning and development requires resilience to anticipated future climate conditions [1–3]. Among the variables driving climate change, rainfall and temperature are used more often as input to hydrologic models. The amount of rainfall and its occurrence determines the gross volume of available resource while temperature is usually considered as direct signal of the evapotranspiration in the area. Performance of GCMs in tropical regions, especially Africa, is relatively less investigated. GCMs outputs enable long-term climate simulation of past-climate and assessment of future climate scenarios in Mara River basin (MRB) [4–7].

As shown in Fig. 1, the transboundary MRB is part and prototype of the Nile River Basin between Kenya and Tanzania. The basin is one of such basins with limited observations of climate and hydrological data. On top of the regional scarcity, the number of functional rain gages in the basin has sharply decreased since 1990. Due to the lack of sufficient rainfall data, recent studies in the basin

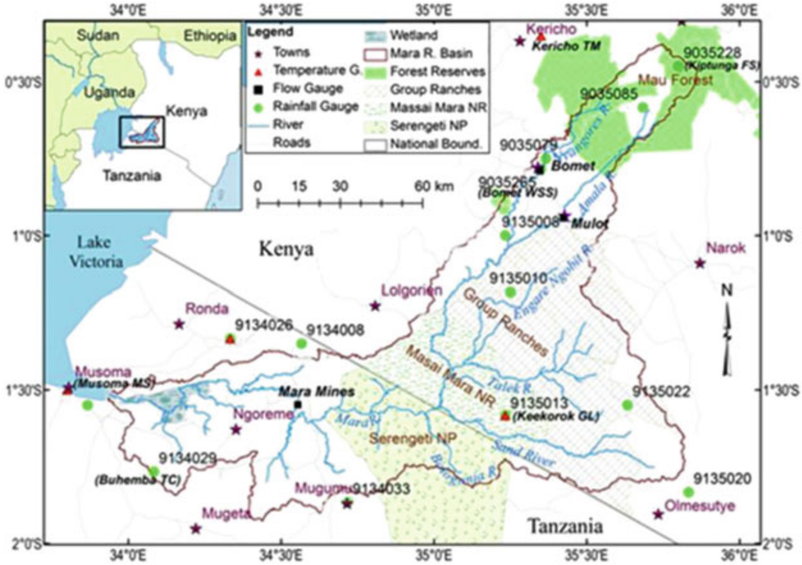

Fig. 1 The Mara River basin location map with major land use types and distribution of monitoring stations [13]

used satellite estimates and GCMs outputs to investigate the hydrological processes and water resources assessment of the basin [7–10]. For example, Soil and Water Assessment Tool (SWAT) was applied on the Nyangores and Amala tributaries of the upper Mara River to assess the impact of land use change using gage rainfall records and satellite RFE from 2002 to 2006 [11, 12].

GCMs are designed for climate simulation at global scale representing major earth systems and regional climate. For data scarce regions, GCMs may prove valuable in simulating past climate condition. Since regional/local hydrologic systems are considerably affected by local physiographic condition, the spatial resolution of GCMs has been a major limitation to direct application [14]. Moreover, hydrologic systems response is highly dependent on surface properties that respond at slower rate compared to atmospheric phenomena. For instance, MRB covers an area of $2° \times 2°$ while the best atmospheric resolution of GCMs with daily atmospheric output in the basin was $1° \times 1.2°$ Latitude and Longitude. Downscaling techniques are commonly used to bridge the spatial disparity of GCMs output and finer scale data required for water resources assessment [15, 16].

Two major classes of downscaling methods, dynamic and statistical, are widely used to cope with the scale problem and extract usable information from GCMs. Wilby et al. [14] suggested that hydrologic impact assessment need to start with direct use of coarse GCM output followed by comparative analysis of the improvements achieved by downscaling procedures. Wilby and Wigley [15] summarized the advantages and disadvantages of these two downscaling techniques. Regional climate models (RCMs) perform dynamic downscaling by nesting and constraining a GCM with local boundary condition of specific region improving the hundreds of kilometers spatial scale to tens of kilometers. However, RCMs are not readily available in the developing regions of the world. Moreover, the need of point climate data in hydrologic assessment requires statistical downscaling on GCM and RCM. The choice of GCMs rainfall output faces two challenges at the very start: what climate model to pick and which downscaling method to apply [16, 17]. Statistical downscaling utilizes statistical properties to build relationship between coarse scale GCM output and the local climate and physiographic variables [14]. The delta and direct statistical downscaling methods [18] were applied in this study. Each downscaling method has certain advantages and disadvantages, and the selection depends on a number of factors such as intended use, resolution of the GCM, size of the study area, and availability of observed data [19].

The increasing variety of RFE, though offers flexibility, is becoming a challenge for users and decision makers. Their performance also varies on the basis of the intended purpose of use, conceptual framework, and assumptions of development. Besides, use of different sources of information to address a specific or similar problem may obstruct dissemination and comparison of findings among researchers to understand the whole system. The reliability of these data sources is seldom verified with observed data. Prior evaluation of estimates may help to utilize the strength of estimates to the best advantage of the project being undertaken and to recognize the limitations as well. Therefore, users need to have a certain preestablished set of criteria to choose a RFE that best represent and able to achieve the objectives of the intended task.

The objective of this chapter is to outline and illustrate simple procedures used to evaluate the potential of RFE and GCMs outputs as an alternative rainfall data sources in the MRB. The procedures outlined in this chapter can be used to assist in understanding the past and planning future water resources development in other watersheds of similar challenge.

2 Study Area

The Mara River flows from the Mau Escarpment in Kenya through Mara-Serengeti protected areas of Kenya and Tanzania and empties to Lake Victoria. The Mara River drains 13, 750 km^2 combined area of south western Kenya and northwestern Tanzania over a stretch of 395 km length (Fig. 1). The highest elevation of the basin is 3,062 m above mean sea level (amsl) at the upstream edge and the lowest is 1,138 m amsl at the downstream flood plain. The two perennial tributaries, Nyangores and Amala Rivers, flow through sections of mixed small- and large-scale agricultural farms and the Mau Forest Reserve, and merge to form the Mara River. The River then joins three ephemeral tributaries Engare Ngobit River, Talek River, and Sand River inside the Massai Mara National Reserve (MMNR) before crossing the Kenya–Tanzania national border. The river then runs through the

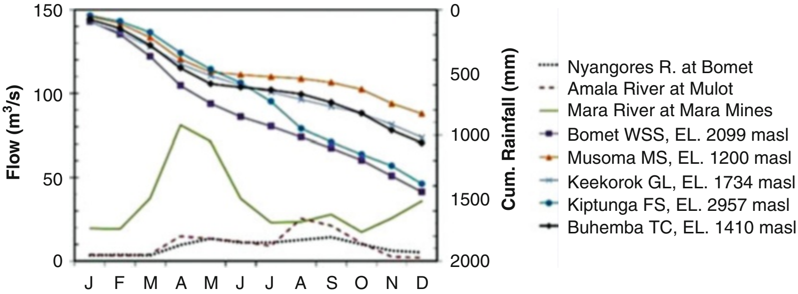

Fig. 2 Average cumulative rainfall and average monthly river flow at selected stations in the MRB (1961–1990) [22]

northern part of Serengeti National Park (SNP) on the Tanzanian side. The SNP is listed as a UNESCO World Heritage site attributed to the unique biannual wild beast migration and pristine biodiversity of the Mara-Serengeti ecosystem. After crossing the SNP, the Mara River joins the last remaining major tributary, Bologonja River, on Tanzanian side and runs through flood plains to Lake Victoria [20].

The social structure and livelihood in MRB is highly dependent on the quantity and quality of the flow in the Mara River and its tributaries. Small-scale agriculture is the largest economic activity engaging 62% of the population over 28% of the available arable land followed by livestock husbandry [21]. Other economic activities in the MRB include large-scale farming, tourism, gold mining, fisheries, logging, and charcoal burning. Major land use types in the MRB are dense forest, bushland, grassland, group ranches, agricultural lands, urban area, and wetland [9, 22].

MRB has bimodal rainfall (Fig. 2) driven by the migration of Inter-Tropical Convergence Zone (ITCZ). The southward migration of the ITCZ causes the short rains in October to December and the returning northward causes the long rains in March to May. The migration of ITCZ is sensitive to variations in Indian Ocean sea surface temperatures that vary from year to year influencing the onset, duration, and intensity of rainfalls in the MRB as well as episodes of El Nino southern Oscillation and La Nina. The annual rainfall decreases with altitude ranging from 1,000 to 1,750 mm in the upper reaches, 900–1,000 mm in the middle, and 300–850 mm at the lower reaches of the river (Fig. 2). Due to orographic effect, windward (Western) side of the basin gets higher rainfall compared to its leeward (Eastern) side. For example, eastern station #9035022 at recorded 660 mm while western station #9035079 recorded 1,440 mm of average annual rainfall. The spatial variation in annual rainfall in the basin indicates orographic effect at the higher altitudes with significant variability across the basin. Amala, Nyangores, and Mara Mines flow gage stations have relatively longer records. The average annual flows at Amala and Nyangores Rivers are 8.1 and 8.5 m^3/s with a standard deviation of 12.4 and 6.5 m^3/s, respectively. The average annual flow at the Mara Mine station is 24 m^3/s with a standard deviation of 22.8 m^3/s.

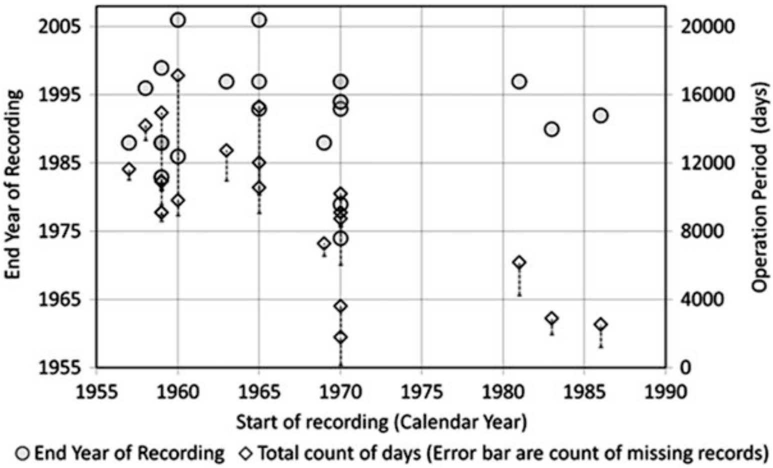

Fig. 3 Start and end year of rainfall recording period for stations in and around the MRB. The end year only corresponds to the availability of data not actual termination of the station

3 Data Set and Methods

3.1 Data Set

The historical observed climate data sets for the MRB were obtained from Kenya Meteorological Department and Tanzanian Meteorological Agency. Twenty rainfall gaging stations were used to represent the spatial variability of rainfall inside and around the basin (Fig. 1). Evaluation of the sufficiency of record length and quality discussed in this chapter was based on the data requirement of the SWAT applied to simulate the rainfall runoff processes [22] and study of uncertainties and impact of climate change [6] in the MRB. Operation period and continuity of observed daily rainfall data were assessed from 1955 to 2006 to see the need to augment/replace the available rainfall data with alternative sources (Fig. 3). These stations were further screened to 13 stations based on their length of record and proximity to the basin. The structure of SWAT version applied for this study takes the closest station to the center of each subbasin cutting down the number of stations needed for simulation to eight. Nine of the 20 rain gage stations are in the MRB and four of the nine were reported to have data after 1994 and only two stations (Bomet WSS and Kiptunga FS) had daily records after 2004.

To assess the possibility of using satellite RFE over the MRB and extend simulation of the rainfall-runoff process beyond 1995, a comparative analysis of RFE and rain gage data sets was done over the intersecting time period. Since RFE were available in 10 days interval from June 1995 to 2000 [23] and the observed rainfall had missing daily records, the monthly total of the two stations in the MRB was compared with the corresponding RFE.

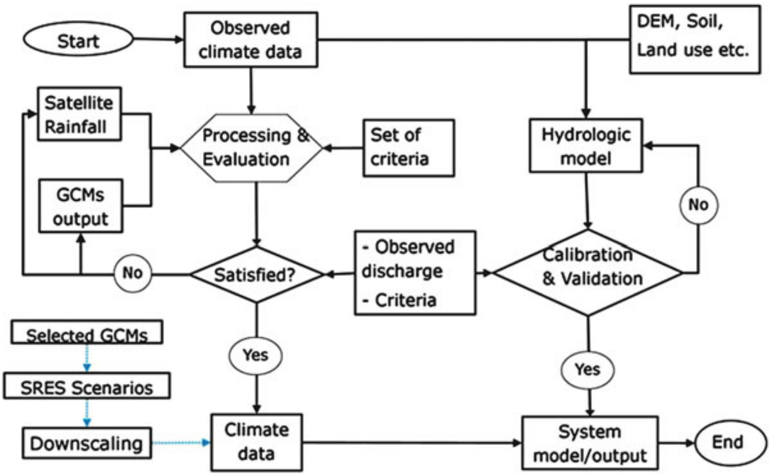

Fig. 4 Evaluation and comparison scheme for satellite rainfall and GCMs rainfall estimates

3.2 Methods

This study has combined two components (Fig. 4). The first component involved assessment of satellite-based RFE and past observed rainfall of the MRB. The second component investigated performance of GCMs in capturing the rainfall process in the MRB. The later component also uses simple statistical downscaling techniques to assess the potential improvement in the performance of raw GCMs outputs.

3.2.1 Satellite Rainfall Estimates

The performance of RFEs may vary with respect to the specific objective(s), the input information used in estimation process, the theoretical basis and validity of assumptions made, the availability and easiness of estimates for water resources applications. The following additional set of criteria were used to select the RFE used in this chapter (Fig. 4): (1) flexibility to various hydrological analysis; (2) convenience and cost to obtain; (3) documentation and user support; (4) previous experience of the estimate's performance, implementation and extent; and (5) capability and limitations in representing the observed rainfall.

The selected RFE was also checked for the following useful features necessary for hydrological modeling and water resources assessment in the MRB: (1) scale, both temporal and spatial; (2) availability of computer software and hardware and skills to use the estimate; (3) simplicity and ease of use, implementation and operation; (4) additional data requirement, resolution with respect to time and record horizon; and (5) presence of additional utilities for input data preparation and output display and interpretation, etc.

The RFE from FEWS NET is a satellite-based RFE database available since June 1995 that combines cloud temperature data from METEOSAT, Global Telecommunication system (GTS) rain gage reports, and other weather inputs. Detailed description on the evolution of RFE is given by Herman et al. [23] and Xie and Arkin [24]. The first algorithm (RFE 1.0) was used from 1998 to 2000, whereas RFE 2.0 developed by Xie and Arkin [24] has been operational since January 2001. RFE 1.0 [23] utilizes cloud top temperature from METEOSAT 5 satellite, GTS rain gage data, model analyses of wind and relative humidity, and orography for the computation of estimates of accumulated rainfall for 10-day period. RFE 2.0 was an improvement over RFE 1.0 including METEOSAT 7, Special Sensor Microwave/Imager (SSM/I) aboard Defense Meteorological Satellite Program Satellites and The Advanced Microwave Sounding Unit on board of NOAA satellites. Free daily RFE grids are available in 0.1° resolution (http://earlywarning.usgs.gov/fews/africa/index.php) for continental Africa and other developing regions of the world.

3.2.2 Global Circulation Models: Selection and Downscaling

Evaluation of GCMs as alternative rainfall information source begins by producing a guideline of model selection and categorical division according to common attributes. The GCMs output used in this chapter were prepared to investigate the impact and uncertainties of climate change on the hydrology of the MRB [6]. A set of six criteria were used to select representative GCMs for the MRB [6]: (1) availability of daily RFE [25]; (2) positive correlation coefficient of monthly average observed and GCM output; (3) mixture of GCMs that overestimate, underestimate, and closer to the average annual observed data in the base period; (4) large or intermediate 30 years average annual range as compared to the range of the observed; (5) heterogeneity of model source such as country or sponsor institution; and (6) ability to capture the observed seasonal variability of average monthly data.

The period 1961–1990 is used as control period for the evaluation of GCMs rainfall outputs as recommended by World Metrological Organization in assessment of climate model performance. Sixteen GCMs with daily simulation outputs of rainfall and maximum and minimum surface temperature were identified [25] (Table 1). Area average monthly rainfall (mm) of stations falling within a grid cell was used to assess cell-wise performance of GCMs to reproduce observed climate pattern over the control period (1961–1990).

The GCMs were first evaluated based on their performance in tracing back the past climate. Annual rainfall data were evaluated and the trend was examined with respect to outputs of GCM. On the basis of analysis of the raw GCM output and observed data, selected GCMs were downscaled using delta and scaling methods [Eqs. (1) and (2)] [6, 18, 19], respectively.

Table 1 List of GCMs used for this impact study with daily mean atmospheric data availability and at least one currently available output for A1B, A2, and B1 SRES scenario [4, 6, 25]

Originating group (country)	GCM	Latitude° × Longitude°
Bjerknes Centre for Climate Research (Norway)	BCCR-BCM2.0	2.8 × 2.8
National Center for Atmospheric Research (USA)	NCAR-CCSM3	1.4 × 1.4
	NCAR-PCM	2.8 × 2.8
Canadian Centre for Climate Modeling and Analysis (Canada)	CGCM3.1(T47)	2.8 × 2.8
Météo-France/Centre National de Recherches Météorologiques (France)	CNRM-CM3	2.8 × 2.8
Commonwealth Scientific and Industrial Research Organization (Australia)	CSIRO-MK3.0	1.9 × 1.9
	CSIRO-MK3.5	1.9 × 1.9
Max Planck Institute for Meteorology (Germany)	ECHAM5/MPI-OM	1.9 × 1.9
US Department of Commerce/NOAA/ Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM2.0	2 × 2.5
	GFDL-CM2.1	2 × 2.5
NASA/Goddard Institute for Space Studies (USA)	GISS-ER	3.9 × 5
Institute for Numerical Mathematics (Russia)	INM-CM3.0	4 × 5
Institut Pierre Simon Laplace (France)	IPSL-CM4	2.5 × 3.75
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC) (Japan)	MIROC3.2 (Med)	2.8 × 2.8
Meteorological Research Institute (Japan)	MRI-CGCM2.3.2	2.8 × 2.8
Hadley Centre for Climate Prediction and Research/Met Office (UK)	UKMO-HadCM3	2.5 × 3.75

$$\text{Delta method}: \quad P_{\text{delta,daily}} = P_{\text{Observed,daily}} \times \left(\frac{\overline{P}_{\text{eval}}}{\overline{P}_{\text{control}}}\right)_{\text{monthly}} \tag{1}$$

$$\text{Scaling method}: \quad P_{\text{Scaling,daily}} = P_{\text{eval,daily}} \times \left(\frac{\overline{P}_{\text{Observed}}}{\overline{P}_{\text{control}}}\right)_{\text{monthly}} \tag{2}$$

where P is rainfall, observed is the observed time series, control is the GCM output of the control period, and eval is the period GCM output were evaluated.

The delta method assumes stationarity in rainfall due to the relative correction factor being applied on the control period observed rainfall. It maintains the number of rainy days and suppresses the daily climate variability of the GCM output. When the evaluation period coincides with the control period, the delta method reproduces the observed daily rainfall. The scaling method, on the other hand, adjusts daily GCM output by long-term average monthly observed and control period GCM output data. The scaling method may produce a new frequency as well as amount of rainfall for the control period. Comparatively, the scaling method offers better flexibility in frequency of climate events but has the limitation of propagating model structural error over the period of analysis. Both methods were used in this study so as to get a comprehensive insight to their applicability simulate past rainfall events of the MRB.

Two representative gage stations from the upper Bomet Water Supply Station (BWSS) and lower reach Buhemba Training Center (BTC) were considered to assess the performance of GCMs and downscaling techniques. Based on the comparative results of downscaled climate data, results were input to SWAT model to evaluate the hydrologic response of MRB to the various GCM outputs.

3.2.3 Analysis and Evaluation of Rainfall Estimates

Evaluation of RFE was first conducted based on statistical relationship between the estimates and the observed rainfall. Acceptable graphical comparison of daily, monthly or annual rainfall time series was followed by quantitative evaluation of RFE with respect to the observed quantity, trend, and variability (and seasonality). Descriptive statistical parameters (mean, standard deviation, range, etc.) and the correlation between the GCMs outputs and observed rainfall were used as primary indicators of performance of GCMs rainfall outputs. Daily RFE are becoming more common, though monthly water balance is more practical in water resources applications. Annual comparisons would help to suppress seasonal/monthly variability between observed and estimated rainfall, but helps to evaluate the quality of the estimate in capturing the annual water balance in the basin. Trend analysis helps to filter outliers in the observed rainfall and check if estimates are able to reproduce such characteristic features. However, a thorough investigation is necessary to ensure whether such deviations are inherent to the model structure or techniques used in generating/estimating the estimate.

Performance of the estimates was assessed through objective functions [Eqs. (3)–(7)] that minimize the distance and optimize the variability between observed event and model result. Mean relative error, MRE [Eq. (5)], was used to evaluate measurement unit independent bias of the model output. It computes the deviation from the observed and reports the expected error per unit of simulation output. A second objective function that optimizes the coefficient of determination, R^2 ([Eq. (7)] to evaluate whether the simulations had optimally reproduced observed variability [26, 27] of the rainfall process while minimizing the overall deviation.

$$\text{Mean relative error (MRE)} = \frac{1}{n}\sum_{i=1}^{n}\frac{|O_i - S_i|}{O_i} \quad (3)$$

$$\text{Root mean square error (RMSE)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2} \quad (4)$$

$$\text{Correlation coefficient, } r = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2 \sum_{i=1}^{n}(S_i - \overline{S})^2}}; \quad r \in [-1, 1] \quad (5)$$

$$\text{Coefficient of determination, } R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})\right]^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2 \sum_{i=1}^{n}(S_i - \overline{S})^2}; \quad R^2 \in [0,1] \quad (6)$$

$$\text{Objective function, Obj}F(O,S) = \begin{cases} \text{minimize}\left(\sum_{j=1}^{k}\text{RMSE}(O,S), \text{MRE}(O,S)\right) \\ \text{Optimize}\left(\sum_{j=1}^{k} R^2(O,S)\right) \end{cases} \quad (7)$$

where O is observed rainfall, S is estimated rainfall, j is the time step, and k is the total number of events.

4 Results and Discussion

4.1 Satellite Rainfall Estimates

More than 11 years (July 1995–December 2006) of monthly rainfall at BWSS and Kiptunga Forest Station (KFS) were compared with point (grid-cell) value and area-average satellite RFE (RFE) over Nyangores and Amala subbasins of MRB (Fig. 5a). Overall, RFEs were higher than observed rainfall in all six pairs of comparison. Over the period of comparison, the observed and RFE (mean, standard deviation) rainfall at KFS were (97.7 mm, 65.4 mm) and (164.1 mm, 108.5 mm), respectively (Fig. 5b). For BWSS, the mean and standard deviation rainfall for the observed and RFE results were (128.4 mm, 83.8 mm) and (183.2 mm, 128.2 mm), respectively (Fig. 5c). On the basis of the results, RFE has not only a consistent overestimation of more than 40% but also inconsistent skill in reproducing rainfall variability ($0.25 \le R^2 \le 0.70$) observed in gage data (Fig. 5d, e) [22].

The best statistics among the six paired comparison was obtained from BWSS vs. Amala subbasin. The mean and standard deviation of subbasin averages of the RFE were higher in the same order as the point sampled RFE values as compared to the observed monthly rainfall depth. The R^2 estimate for KFS vs. Amala subbasin was 0.2. When KFS was regressed with the average of Nyangores and Amala subbasins, R^2 values of 0.44 and 0.55 were obtained, respectively. The result might suggest that BWSS would better represent rainfall over the two adjacent subbasins as compared to the KFS at the northern tip of the Amala subbasin. On the contrary, the orographic effect of relatively higher elevation (Fig. 2) might be responsible for the difference observed in the analysis.

The relatively low performance at KFS could be due to the number of missing rain gage data or the reduced performance of RFE to capture local orographic rainfall. Given the uncertainties in both RFE and gage data, the analysis showed that RFE repeats the trend of gage data as claimed by Mango et al. [7]. Since only

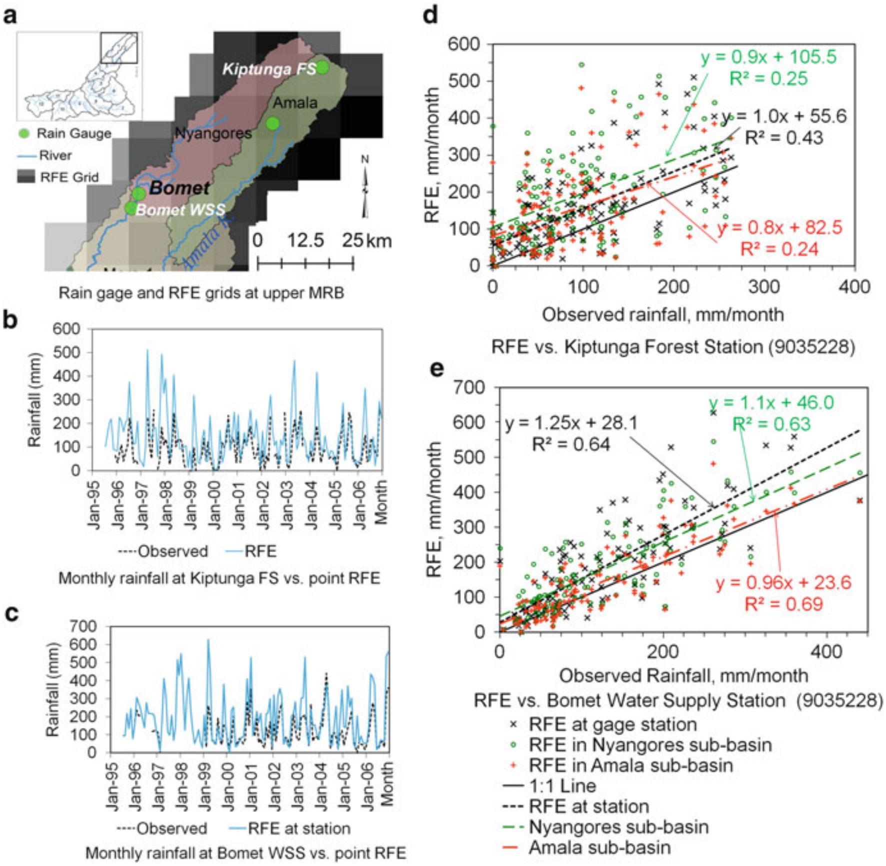

Fig. 5 Monthly RFE values versus observed rain gage records for the upper MRB from July 1995 to December 2006. RFE values were extracted from RFE grids corresponding to the locations of rain gage, and averaged over Nyangores and Amala subbasin area. Linear trend lines were fitted [22]

two stations were considered, the results are diagnostic to the potential use of RFE as an alternative rainfall data in hydrologic analysis [28]. Accordingly, comparing (extending) hydrological simulation results that use rainfall input from rain gage and RFE may compromise the otherwise meaningful output of independent outputs.

4.2 GCMs Rainfall Outputs

Sixteen GCMs with daily outputs of atmospheric data (rainfall, maximum and minimum temperature) were considered (Table 1). Observed monthly rainfall data over the control period (1961–1990) was used to assess the capability of these GCMs in reproducing past climate of the MRB (Fig. 6a). Nine of the 16

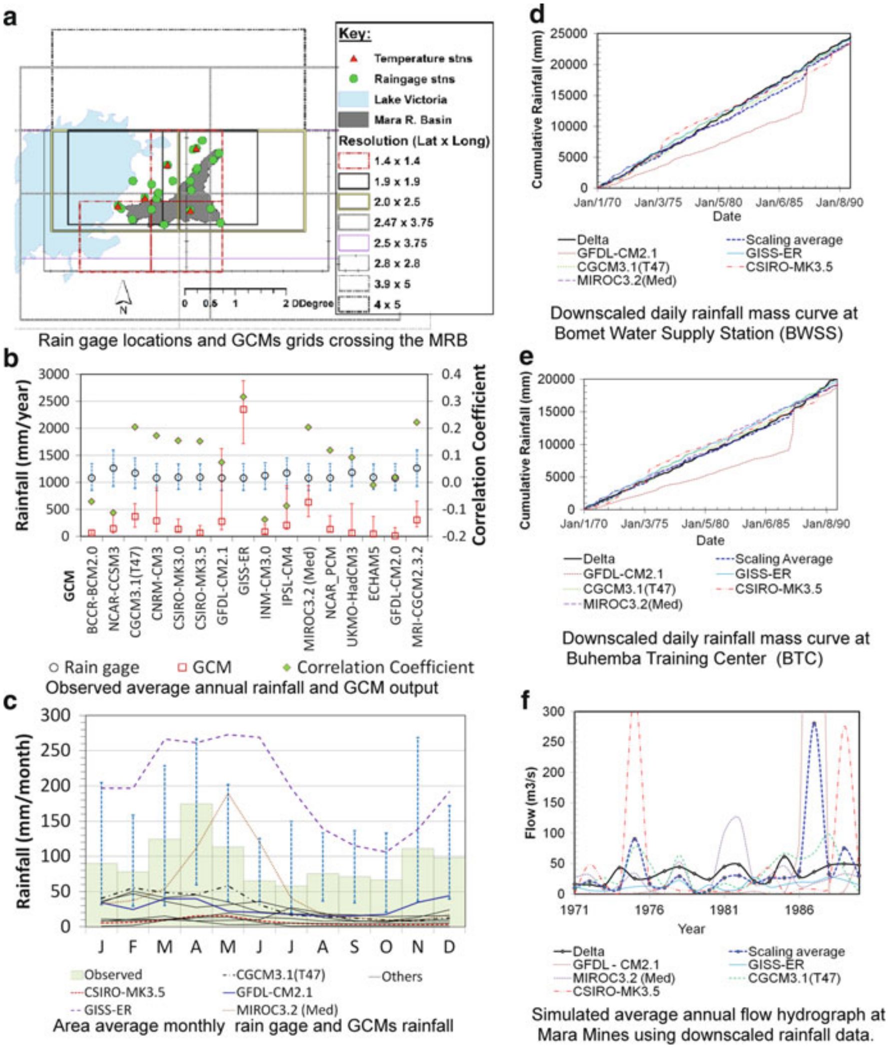

Fig. 6 (**a**) Area-average gage and GCM output rainfall from 1961 to 1990, (**b**) and (**c**) are based on raw outputs from 16 GCMs. Error bars correspond to minimum and maximum for observed (*dash*) and GCM output (*solid*) from 1961 to 1990 [4, 25]. (**d–f**) are based on downscaled daily rainfall from five selected GCMs over 20 years (1970–1990). Scaling average is the average of analysis result of five GCMs output

models were positively correlated with the monthly observed, but the correlation coefficients are all below 0.5 (Fig. 6b). The average annual RFE of the GCMs also indicated a significant underestimation of the observed average annual rainfall (Fig. 6b) of 30 years control period. Only GISS-ER had considerably overestimated rainfall (200%) with the highest correlation coefficient. The average annual rainfall from GCMs fell below the 30 years minimum of the observed except for GISS-ER and MIROC3.2 (Med). On the basis of the observed monthly (seasonal) variability, none of the models were able to simulate the rainfall pattern of the MRB (Fig. 6c). The overall skill of the GCMs in capturing the MRB rainfall was found to suggest statistical downscaling based on the observed data to better represent the climate of the river basin.

On the basis of prior established set of criteria, five GCMs [GCM3.1 (T47), CSIRO-MK3.5, GFDL-CM2.1, GISS-ER, and MIROC 3.2 (Med)] were selected for statistical downscaling and further hydrological evaluation. The scaling and delta downscaling methods were applied on selected GCMs output over the 21 years (1970–1990) rainfall output. Results showed that performance varies with the GCM and downscaling technique suggesting the choice of particular GCM and downscaling over the other may depend on the purpose that the rainfall information is required for (Fig. 6c–e). On the basis of the current GCMs output in MRB, the RFE are less reliable with poor skill to simulate the MRB rainfall driven by migration of ITCZ, but they offer a longer time span of data to the past and future.

The delta downscaling method preserved the historical daily rainfall over the period of analysis. The scaling method, on the other hand, produced new set rainfall characteristics such as the number of rainy days, quantity, and sequence of rainfall events (Fig. 6d, e). Accordingly, the runoff response using different GCMs outputs and downscaling method produces different hydrographs (Fig. 6f).

The daily rainfall mass curves prepared over 21 years for the observed (delta) and scaling method reflect on the characteristics of the GCMs performance at the two stations, upstream and downstream of the Mara River. The mass curve from the scaling method at BWSS showed overestimation of the daily rainfall in the 1970s and underestimation afterwards, whereas at Buhemba Training Center (BTC) the scaling method overestimated for the most part of the 21 years daily estimation. GFDL-CM2.1 has significantly deviated from the other models in estimating the daily rainfall until 1987 and jumped in just a few days to match with the steady curve of the other four GCMs. This pattern may suggest either model error or simulation of global climate perturbation by the particular GCM. However, such attributes may not fully serve to generate realistic RFE of the past unless verified by historical observation.

Selected GCMs outputs downscaled and input to the SWAT model to compare the extent that downscaling methods will influence the rainfall runoff process in the MRB. On the basis of the average annual hydrographs (Fig. 6f) the scaling method had produced unique hydrograph for each of the five GCMs considered. The average of the five hydrographs was plotted along with the hydrograph from the observed (delta) rainfall. The peak annual flows correspond to the jumps observed in the rainfall mass curves (Fig. 6d, e). The results suggest that rainfall data generated using the scaling method may not represent the past climate condition but can shade light on how the basin would have responded, had those rainfall events occurred. Hence, the flow hydrographs can be used simply as a potential realization in the ensemble of probable rainfall events for water resources planning purposes.

5 Conclusions

Scarcity and inconsistency of observed rainfall data has been a major limitation in water resources study. Alternative rainfall data sources are being used to circumvent the challenge with limited verification of the techniques employed or reliability of the estimates. Satellite RFE and general circulation models (GCMs) are becoming the source of rainfall information in the developing regions of the world. This chapter outlined basic evaluation and comparison techniques applied to verify the reliability of RFE (from FEWS-NET) and selected GCMs outputs as an alternative rainfall data sources in the MRB.

RFEs are appealing to users due to the continuity in time, spatial coverage and suitability of gridded data to standard GIS processing tools in water resources. Compared to observed rainfall, RFE values were generally higher (>40%) than gage rainfall and displayed nonuniform skill in reproducing monthly rainfall variability and amount. Despite the limitations observed in the two stations, RFE has a promising potential to supplement the existing observed rainfall data for regions that lack sufficient and reliable amount of observed data for the intended purpose.

The GCMs are designed to simulate global climate and may be used as a tool for learning about the rainfall pattern of particular place. The performance of the GCMs varies with the GCM and downscaling technique suggesting the choice of particular GCM and downscaling over the other may depend on the purpose that the rainfall information is required for. On the basis of the current GCMs output considered for the MRB, the RFE are less reliable with poor skill to capture the migration of ITCZ, but they offer a longer time span to generate rainfall information in the past (and future). Comparison of the delta and statistical downscaling methods applied on the daily rainfall outputs of selected GCMs have improved the quality of rainfall information extracted from GCMs. Since hydrological response of a watershed at a particular time depends not only on the amount, duration, and frequency of rainfall but also on the antecedent rainfall event; the delta method can recapture the past and be useful to fill data gaps in the past. The scaling method, on the other hand, alters the characteristics of daily rainfall events in the past that may require careful consideration to use as alternative data source for sensitive water resource applications.

On the basis of the hydrological assessment using rain gage data, RFE and GCMs output in the MRB, comparison of results from studies using different rainfall data input may potentially result in different pictures of the water resources of the basin. Since few stations were considered in the analysis, the findings are hardly conclusive rather diagnostic that further investigation is necessary to exploit the potential of RFE and GCMs as alternative data sources. These sources of rainfall information may supplement watersheds/stations with insufficient amount of observed data. The evaluation methods can also be applied to other climate data as well as watersheds of similar data challenge as the MRB. Finally, the current advances in remote sensing and evolution of GCMs is continuously improving quality and availability of reliable rainfall as well as other climate data.

Acknowledgments The authors acknowledge Global Water for Sustainability (GLOWS) program and the USAID for their financial support to conduct the field data collection component of this study. Authors also thank Worldwide Fund for Nature Offices (WWF) in Kenya and Tanzania, Kenyan and Tanzanian Ministry of Water and Irrigation, and Lake Victoria South Catchment Area of Kenya's Water Resources Management Authority. The authors also thank Michael McClain, Daniel Gann, Amanda Subalusky, Doris Ombara, Christopher Dutton, and Zachary Maritim from WWF-Kenya and Joseph Kiprono Terere from Mara TIWRM for their support at different stages of this study. The authors would like to acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modeling (WGCM) for their roles in making available the WCRP CMIP3 multi-model data set. Support of this data set is provided by the Office of Science, U.S. Department of Energy. Finally, the authors would like to acknowledge financial support through Dissertation Year Fellowship provided by the Graduate School of Florida International University.

References

1. C-y X (1999) Climate change and hydrologic models: a review of existing gaps and recent research developments. Water Resour Manag 13(5):369–382
2. Dibike YB, Coulibaly P (2005) Hydrologic impact of climate change in the saguenay watershed: comparison of downscaling methods and hydrologic models. J Hydrol 307(1–4):145–163
3. Leavesley GH (1994) Modeling the effects of climate change on water resources—a review. Clim Chang 28(1):159–177
4. IPCC (2007) In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
5. Collier P, Conway G, Venables T (2008) Climate change and Africa. Oxf Rev Econ Pol 24 (2):337–353. doi:10.1093/oxrep/grn019
6. Dessu SB, Melesse AM (2012) Impact and uncertainties of climate change on the hydrology of the Mara River basin, Kenya/Tanzania. Hydrol Process (in press). doi:10.1002/hyp.9434
7. Mango LM, Melesse AM, McClain ME, Gann D, Setegn SG (2011) Land use and climate change impacts on the hydrology of the upper Mara River basin, Kenya: results of a modeling study to support better resource management. Hydrol Earth Syst Sci 15(7):2245–2258
8. Hoffman CM, Melesse AM, McClain ME (2011) Geospatial mapping and analysis of water availability-demand-use within the Mara River basin. In: Melesse AM (ed) Nile river basin: hydrology, climate and water use, vol Part I, 1st edn. Springer, Dordrecht, pp 359–382
9. Mati BM, Mutie S, Gadain H, Home P, Mtalo F (2008) Impacts of land-use/cover change on the hydrology of the transboundary mara river, Kenya/Tanzania. Lakes Reservoirs Res Manag 13:169–177
10. Mango LM (2010) Modeling the effect of land use and climate change scenarios on the water flux of the upper mara river flow, Kenya. Florida International University, Miami
11. Mango LM, Melesse AM, McClain ME, Gann D, Setegn SG (2011) Hydro-meteorology and water budget of the Mara River basin under land use change scenarios. In: Melesse AM (ed) Nile river basin: hydrology, climate and water use, vol 1, 1st edn. Springer, Dordrecht, pp 39–68
12. Mango LM, Melesse AM, McClain ME, Gann D, Setegn SG (2011) Land use and climate change impacts on the hydrology of the upper Mara River basin, Kenya: results of a modeling study to support better resource management. Hydrol Earth Syst Sci 15(7):2245–2258
13. Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models. Part I—a discussion of principles. J Hydrol 10(3):282–290

14. Wilby RL, Charles SP, Zorita E, Timbal B, Whetton P, Mearns LO (2004) Guidelines for use of climate scenarios developed from statistical downscaling methods. Supporting material of the Intergovernmental Panel on Climate Change (IPCC), prepared on behalf of Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA)
15. Wilby RL, Wigley TML (1997) Downscaling general circulation model output: a review of methods and limitations. Progr Phys Geogr 21(4):530–548. doi:10.1177/030913339702100403
16. Xu C-Y (1999) From gcms to river flow: a review of downscaling methods and hydrologic modelling approaches. Progr Phys Geogr 23(2):229–249. doi:10.1177/030913339902300204
17. Maraun D, Wetterhall F, Ireson AM, Chandler RE, Kendon EJ, Widmann M, Brienen S, Rust HW, Sauter T, Themeßl M, Venema VKC, Chun KP, Goodess CM, Jones RG, Onof C, Vrac M, Thiele-Eich I (2010) Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user. Rev Geophys 48(3):RG3003
18. Lenderink G, Buishand A, Van Deursen W (2007) Estimates of future discharges of the river rhine using two scenario methodologies: direct versus delta approach. Hydrol Earth Syst Sci 11 (3):1145–1159
19. Graham L, Andreasson J, Carlsson B (2007) Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods: a case study on the lule river basin. Clim Chang 81:293–307
20. Mango LM, Melesse AM, McClain ME, Gann D, Setegn SG (2011) Hydro-meteorology and water budget of the Mara River basin under land use change scenarios. In: Melesse AM (ed) Nile river basin: hydrology, climate and water use, vol 1, 1st edn. Springer, Dordrecht, pp 39–68
21. Lamprey RH, Reid RS (2004) Expansion of human settlement in Kenya's maasai mara: what future for pastoralism and wildlife? J Biogeogr 31(6):997–1032
22. Dessu SB, Melesse AM (2012) Modeling the rainfall-runoff process of the Mara River basin using swat. Hydrolog Process 26(26):4038–4049. doi:10.1002/hyp.9205
23. Herman A, Kumar VB, Arkin PA, Kousky JV (1997) Objectively determined 10 day African rainfall estimates created for famine early warning systems. Research and Data Systems Corporation, and National Centers for Environmental Prediction, Climate Prediction Center
24. Xie P, Arkin PA (1997) Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull Am Meteorol Soc 78 (11):2539–2538
25. Meehl GA, Covey C, Delworth T, Latif M, McAvaney B, Mitchell JFB, Stouffer RJ, Taylor KE (2007) The wcrp cmip3 multi-model dataset: a new era in climate change research. Bull Am Meteorol Soc 88:1383–1394
26. White KL, Chaubey I (2005) Sensitivity analysis, calibration, and validations for a multisite and multivariable swat model1. J Am Water Resour Assoc 41(5):1077–1089
27. Setegn SG, Srinivasan R, Melesse AM, Dargahi B (2009) Swat model application and prediction uncertainty analysis in the lake tana basin, ethiopia. Hydrolog Process 24(3):357–367
28. Jayakrishnan R, Srinivasan R, Santhi C, Arnold JG (2005) Advances in the application of the swat model for water resources management. Hydrolog Process 19(3):749–762

Projected Future Precipitation Scenarios for a Small Island State: The Case of Mauritius

Mohammed H.I. Dore and Rajiv G. Singh

Abstract The economies of small island developing states (SIDS) can be sensitive to climate variability in the future. In this chapter, we use four of IPCC's Fourth Assessment Global Circulation Models (GCMs) to produce precipitation projections for the next 90 years for the small island state of Mauritius. We focus our projections on the Vacoas-Phoenix region of this island because (a) this is the central region of the island, where all the major water reservoirs are located, (b) this region has normally higher precipitation and a higher variability of precipitation than the coastal regions, and (c) the rainfall in the mountainous part of this region feeds most of the rivers. Thus we expect that the groundwater recharge rate is probably more sensitive to precipitation in this region. Our results show that historically wetter months are likely to become wetter while drier months could become even drier than currently observed, but the net annual precipitation is likely to decline. This can have a significant impact on the growing tourist industry in the region which is likely to strain its water resources.

Keywords Global circulation models, Impacts on water resources, Mauritius, Precipitation projections, Small island states, Water management

Contents

M.H.I. Dore (✉) and R.G. Singh
Climate Change Lab, Department of Economics, Brock University, St Catharines, ON, Canada L2S 3A1,
e-mail: dore@brocku.ca; rajivgsingh@hotmail.com

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*, Hdb Env Chem (2013) 25: 47–66, DOI 10.1007/698_2013_221,

1 Introduction

Climate change can impact countries in a number of ways, and mitigating and/or adapting to climate change is likely to be costly. According to the IPCC's Fourth Assessment [1], by 2020, 75–250 million people are expected to suffer from water stress as a direct result of climate change in Africa while yields from rain-fed agriculture is projected to decrease by 50%. This can compromise food security and worsen the state of malnutrition in Africa. In the same continent, the IPCC's Fourth Assessment suggests that low-lying coastal areas are likely to be adversely affected by rising sea levels by the turn of the century and that the cost of adaptation could amount up to 10% of GDP. The intensity and frequency of many extreme weather events such as cyclones, flash floods, severe droughts, heat and cold waves are projected to increase.

Small island developing states (SIDS) account for less than 1% of global greenhouse gases (GHG) emissions and yet are more vulnerable to the effects of climate change because of their lack of financial resources and the technology necessary to adapt [2]. They are also physically small and are surrounded by large expanses of ocean. Most small island states like Mauritius and Reunion Island have limited natural resources and are more prone to natural disasters and extreme events. They are also characterized by vulnerable economies due to large population densities, high population growth rates, poorly developed infrastructure, limited funds, and lack of trained human resources [3].

SIDS are also faced with serious challenges due to changes in sea levels, structural shifts in precipitation and temperature, as well as localized or microclimate shifts. Low-lying islands or regions are particularly vulnerable to sea level rises due to climate change [4]. For small island states, sea level rise would affect freshwater sources, agriculture, fisheries, tourism, and infrastructure and can have the detrimental effect of loss of land due to a rising sea level [5]. Mauritius is a small island state located south-east of Madagascar in the Indian Ocean with a small population of about 1.5 million people. For Mauritius, there are already signs of rising sea levels within the last 60 years. A rise of approximately 1.5 mm/year has been reported at the island's capital, Port Louis, between 1950 and 2007 while a rise of 1.3 mm/year has been experienced at Rodrigues during the same time period [6]. However, between the 1987 and 2007 period, Port Louis has experienced an average rise of 2.1 mm/year during the last 10 years indicating that the rate of the sea level rise has been increasing [6]. This makes Mauritius particularly vulnerable to sea level rise since most hotels are located in close proximity to the coast and almost half of Mauritius' residents live within 1 km of the coast.

Small island states would also be particularly vulnerable to extreme precipitation events which are projected to increase in the future and can represent a high adaptation cost relative to GDP [2]. For instance in Mauritius, there has been an increase in the number of extreme weather events including heavy rainfall and stronger cyclones over the last two decades [6], and increased flash flooding and drier winter seasons that include severe droughts [7]. In 1994, tropical cyclone Hollanda, the most intense cyclone in 19 years to impact Mauritius, caused two deaths, and thousands lost their homes, while damages amounted to US$135 million, which is approximately a 10% decrease in GDP. Other small island states have experienced a similar level of destruction caused by extreme weather events. More recently in 2005, Hurricane Ivan, the worst tropical system since 1955 for the small island state of Grenada, killed 28 people, caused damage to 90% of all housing and 90% of guest rooms in the hotel sector; this was equivalent to a loss of approximately 29% of GDP. Furthermore, the hurricane caused loss in the agricultural sector of about 10% of GDP and an overall damage estimated at twice the value of Grenada's GDP in 2005 [2].

Although the IPCC's Fourth Assessment projects increases in precipitation during "wetter" months [1], small island states lack the ability to store the increase in precipitation or rather they lack the resources to expand their storage capabilities. The problem therefore lies in coping with water management during the drier months where precipitation is projected to decrease and longer periods of zero rainfall will become more frequent. In recent years, the number of consecutive days with zero precipitation has been increasing while the number of consecutive days of above-zero precipitation has been decreasing in Mauritius while the transition period between drier months and wetter months has increased indicating a longer dry season [6]. The delay in the onset of the rain during the wetter months added strain on various sectors of Mauritius including the agricultural and tourism sectors. However, although the number of above-zero precipitation days are decreasing the number of heavy rainfall events are increasing and this can also have an adverse effect on socioeconomic activities [6].

A baseline study conducted in Port Louis, Mauritius, suggests that there are signs that annual rainfall has been declining over the 1960–2006 period at an average of 7.7 mm/month (8.7%) per decade [7]. Precipitation projections in the baseline study suggest both an increase and decrease in mean annual rainfall in the range of −20 to +24%, depending on the model used in the projection. However, the future projected precipitation suggests that seasonal rainfall tended towards a decline while southern islands tended to have decreases in rainfall in all seasons [7]. Precipitation during heavy rainfall events shows both an increase and decrease within a range of −13 to +5% but a stronger tendency towards a seasonal decrease

[2, 7] suggests that there is strong evidence that water resources in all of the SIDS could become seriously compromised and tourism, which is a major contributor to GDP and employment in most of these states, could be seriously affected by climate change. For example, accelerated beach erosion, loss of cultural heritage from flooding and extreme events, water shortages, and increased vector-borne diseases can deter potential tourists. In addition, subsistence and commercial agriculture which require careful use of water resources can be affected by drought and flooding as well as soil salinization due to rising sea levels [2].

There is little doubt that Mauritius will face challenges from climate change in the future. Traditionally dependent on the sugar production, Mauritius now has a manufacturing sector and a growing tourist attraction due to its equitable climate and plenty of sandy beaches. Indeed, receipts from tourism can account for as much as 13% of the Gross Domestic Product in 2011 for Mauritius [8]. The tourist industry is likely to strain its water resources as it appears that the amount of water drawn from its aquifers could soon exceed the recharge rate. About half of water supplied to residents comes from groundwater sources while the remainder comes from surface sources including reservoirs in Mare Aux Vacoas, Piton du Milieu, La Nicoliere, Port Louis Municipal Dyke Dam, and Riviere du Poste [7]. However, demand has been increasing by an average of 3% per year over nearly the last three decades and the trend is likely to continue up to 2025 [7]. The increased demand may not be met even if expansion programs are in place for reservoirs and water catchment facilities since the island is susceptible to many climate and non-climate related factors such as cyclone activity in the southern Indian Ocean which frequently causes heavy damage, declining annual precipitation, increased mean temperature which can lead to increased evaporation rates particularly at surface reservoirs, sea level rise which increases the salinity of groundwater sources and increase in population which can be accompanied by increases in agrochemicals to boost food supply and which can pollute groundwater sources. The future development of Mauritius will require a careful water resource management policy. This policy will have to take into account the possible future impacts of climate change and how it may affect future precipitation.

The objective of research reported in this chapter is to quantify expected changes in precipitation over the next 100 years for Mauritius using four Global Circulation Models (GCMs) and the best available statistical downscaling methods. It is expected that this quantification serves as a prelude to developing a policy of adaptation and conservation of water resources in Mauritius. The Vacoas-Phoenix region of Mauritius was chosen as focal point of the study because (a) this is the central region of the island, where all the major water reservoirs are located, (b) this region has normally higher precipitation and a higher variability of precipitation than the coastal regions, and (c) the rainfall in mountainous part of this region feeds most of the rivers; thus it is anticipated that the groundwater recharge rate is probably more sensitive to precipitation in this region.

Fig. 1 The Vacoas-Phoenix and surrounding regions of Mauritius [9]

2 Mauritius: Historical Climate Patterns

The island of Mauritius is situated about 1,100 (km) east of the midpoint of Madagascar. The Vacoas-Phoenix region lies at 57°29′ East and 20°18′ South (see Fig. 1 for key regions). The distance from the northern tip of the island to the southern tip is approximately 61 km long while the east–west distance measures 46 km wide and a total land area of about 2,040 km^2.

Mauritius only has two seasons: summer and winter. Summer months last from November to April (which also span most of the cyclonic season) while winter months last between May and October and receive less precipitation compared to the summer months. Mauritius collects most of its water during the cyclonic season. Our analysis uses the actual observed precipitation patterns in the Vacoas-Phoenix region between 1961 and 1990, which is the baseline period recommended by the IPCC. Figure 2 shows the average precipitation per day for each month for the 1961–1990 period while Fig. 3 shows the average precipitation per day for three 10 year periods of the baseline period for the Vacoas region.

There is indication that even during the baseline period some shift in climate has occurred. This is consistent with IPCC Fourth Assessment which suggests rising

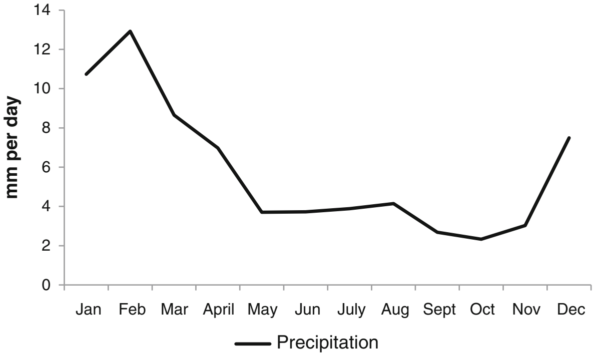

Fig. 2 Precipitation for the Vacoas region of Mauritius: 1961–1990

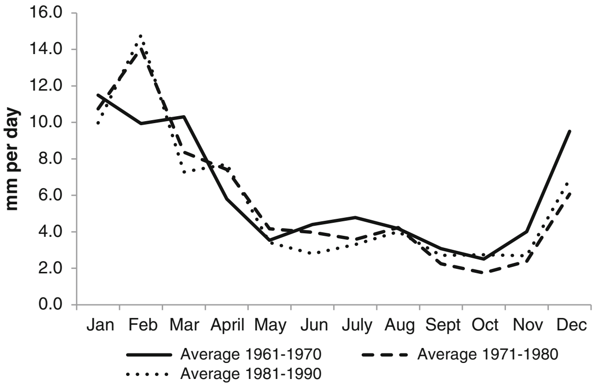

Fig. 3 Precipitation in Vacoas region of Mauritius over three decades in baseline period

GHG emissions within the base period that can affect the climate [1]. Compared to the 1961–1970 period, we observe an increase in precipitation for February and April, historically wetter months, in the next two decades. May to December seem to experience a decline in precipitation compared to 1961–1970 levels. The average total precipitation per year during the 1961–1970 period was 2,231 mm and this is higher than the 1971–1980 (2,079 mm) and 1981–1990 (2,055 mm) precipitation totals per year. The overall average precipitation between 1961 and 1990 is 2,122 mm/year. Since Mauritius collects most of its water during the cyclonic season, Mauritius may already be suffering from stress due to reduced water resources based on the observed trends in the baseline period.

3 Projection Patterns for Mauritius

In the IPCC Special Report on Emission Scenarios (SRES), global GHGs are expected to increase by 25–90% between 2000 and 2030 and up to 140% (as a percent of 2,000 emissions levels) for CO_2 emissions by 2050 depending on the scenario used [1]. There are four scenario families in SRES: A1, A2, B1, and B2. We use the A2 family of the SRES scenarios. A2 assumes a very heterogeneous world with high population growth rates but low economic and technological development. We consider this scenario to be slightly conservative in its assumptions on population growth, economic development, and technological change. In contrast, the A1 storyline assumes a high rate of economic growth and technological advancement while population growth peaks mid-century. The B1 scenario also assumes population growth peaks mid-century but rapid changes in the structure of the economy would be due to a shift towards the services and information sectors. The B2 scenario assumes a continuous population growth but at a smaller rate than in the A2 scenario and an emphasis towards localized solutions towards economic, social, and environmental sustainability [1]. However, according to the IPCC no one scenario is more likely to occur than another.

The following GCMs are used in our study to project precipitation for 90 years into the future:

1. The Hadley Centre Global Environment Model version 1 (HADGEM1), model from the United Kingdom Meteorological Office.[1] The spatial resolution of the HADGEM1 is 1.25° in the horizontal or latitude and 1.875° in the longitude or vertical component.
2. The Coupled Global Climate Model[2] (CGCM3) version T47 from the Canadian Centre for Climate Modelling and Analysis (CCCma). The spatial resolution of the surface grid is approximately 3.75° in both the latitude and longitude.
3. ECHAM 5OM from the Max Planck Institute for Meteorology.[3] The spatial resolution is approximately 2.8° in both the latitude and longitude.
4. The Australian Commonwealth Scientific and Industrial Research Organization version Mark 3.5 (CSIRO Mk3.5). The resolution for the atmospheric component of the model is 1.875° in both the latitude and longitude.[4]

A combination of GCM data and actual observed data is used in order to downscale precipitation projections for Vacoas-Phoenix. It is assumed that precipitation changes in the future are multiplicative. We employ a simple yet intuitive approach to downscaling precipitation. The steps are as follows:

[1] For details on the HADGEM1 model see Refs. [10–12].

[2] For details see Refs. [13, 14].

[3] The "EC" part of the ECHAM refers to the European Centre for Medium-Range Weather Forecasts while the "HAM" portion refers to the place the model was developed – Hamburg. For details of the model see Ref. [15].

[4] For details see Ref. [17].

3.1 Step 1

We fit the best Box-Jenkins ARIMA model[5] to the base years (1961–1990) of the respective GCM models. We choose the ARIMA methodology because it utilizes autocorrelations and partial autocorrelations in the data set in order to produce forecasts and can be used on any type of series: seasonal, trend, cyclical, stationary, and nonstationary [16]. The fitted values obtained for the base years can be denoted as $A_{m,y}$, where m is the month and y is the year. The idea here is that the baseline years would be characterized by a set of autoregressive processes, innovative or random processes, or a mixture of both.

The Schwarz-Bayesian Information Criteria (SBC) is used to obtain the best ARIMA model since it chooses the simplest model over a range of alternatives. As is customary in the climate change literature, we also divide each GCM models into three time slices: the 2020s, 2050s, and 2080s from which, only one time slice is considered at any given point. The 2020s time slices are the 30 years between 2010 and 2039 (inclusive) while 2050s are the 30 years between 2040 and 2069. The 2080s therefore runs from 2071 to 2099.

3.2 Step 2

The mean of each month (M_{m}) over the 30-year period for the fitted values, $A_{m,y}$, is then calculated. For example, the mean for January can be calculated as follows:

$$M_1 = \frac{\left(A_{1,1961} + A_{1,1962} + \ldots + A_{1,1990}\right)}{30}.$$

The same procedure is carried out to calculate the mean for the other 11 months.

3.3 Step 3

The GCM values (denoted as $G_{m,y}$) are then divided by the mean of the fitted values, M_y, obtained in Step 2 in order to obtain multipliers, $L_{m,y}$, for each month of each year in each time slice. These are the magnitude of change in precipitation expected in the future time slices. They can be thought of as the change in the projected future values of GCM relative to a "modeled" baseline period; "modeled" in the sense that

[5] ARIMA methodology developed by Box and Jenkins [18].

the baseline period is characterized by a particular data generating process. Since each time slice is 30 years, there is one multiplier for each month in each year for a total of 360 multipliers for each time slice.

$$L_{m,y} = G_{m,y}/M_m$$

3.4 Step 4

Multiply the "multiplier" by the observed base, $O_{m,y}$, to obtain the downscaled values, $D_{m,y}$

$$D_{m,y} = L_{m,y} \times O_{m,y}$$

Localized conditions are represented by observed precipitation for the Vacoas region. The magnitude of the projected increase in precipitation is the relative change between the future GCM values (which contain information on GHG forcing and other factors that will affect climate change for the particular grid box but which is too large to accurately represent localized conditions of any given area in Mauritius) and a modeled base period. The downscaled projections are therefore local or observed precipitation inflated (or deflated) by the degree in which climate change affects the local as well as nearby surrounding regions.

4 Precipitation Projections

The standard notation of ARIMA models with both seasonal and nonseasonal components is ARIMA$(p,d,q) \times (P,D,Q)$, where (p,d,q) is the order of the nonseasonal component and (P,D,Q) the order of the seasonal component. P and p are the seasonal autoregressive and nonseasonal autoregressive components, respectively, while Q and q are the seasonal and nonseasonal random shocks, respectively. D and d are first differences in the seasonal and nonseasonal levels of the series. The augmented Dickey–Fuller test indicates that first differences of either the seasonal and nonseasonal levels are not required for all of the GCM baseline data.[6] The SBC was calculated for a range of models (up to three lags in the seasonal and nonseasonal autoregressive and random shocks components and up to two lags in mixed models) and the model with the lowest SBC was chosen. We use the SBC criterion since it selects simpler models over more complex ones.

[6] Not shown but can be provided by the authors.

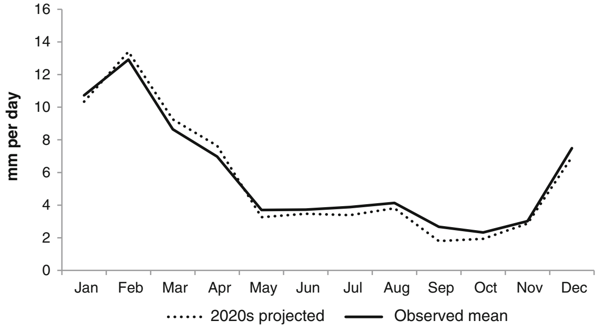

Fig. 4 Observed mean vs. 2020s downscaled precipitation for Mauritius: HADGEM1

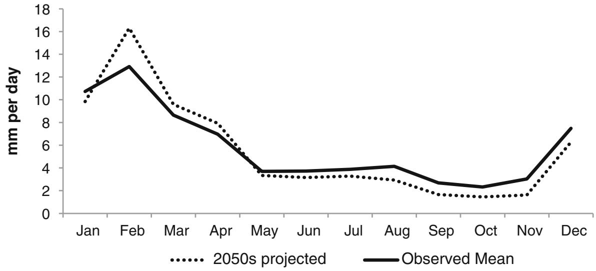

Fig. 5 Observed mean vs. 2050s downscaled precipitation for Mauritius: HADGEM1

For the HADGEM1 GCM, the model chosen in this case was the ARIMA (2,0,0) $\times$ (1,0,1) which suggests some autoregressive characteristics in the levels (i.e., the last 2 month's precipitation is strongly correlated with the current month's precipitation level), some autoregressive characteristics in the seasonal component (i.e., last year's January precipitation is highly correlated with the current year's January precipitation levels), and some seasonal random shocks (i.e., there are some random shifts in precipitation over one season to the next). For the CGCM3 T47 GCM, the model chosen was the ARIMA (1,0,0) $\times$ (1,0,1) which is similar to the model chosen for the HADGEM1 GCM. For the CSIRO Mk3.5 and ECHAM 5OM GCMs, the models chosen were the ARIMA (0,0,0) $\times$ (1,0,1) and ARIMA (0,0,0) $\times$ (3,0,0), respectively.

4.1 HADGEM1 Downscaled Results

The downscaled precipitation for the 2020s, 2050s, and 2080s using the HADGEM1 GCM is shown in Figs. 4, 5, and 6.

These projections indicate that months that receive relatively high precipitation totals, February to April in particular, can become wetter or receive higher levels of precipitation in the future. Historically dry months such as May to October are projected to become drier. Moreover, the projections indicate that the further into the future the drier months become increasingly drier and the so-called wet months

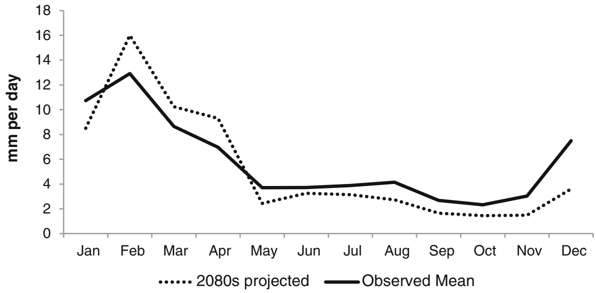

Fig. 6 Observed mean vs. 2080s downscaled precipitation for Mauritius: HADGEM1

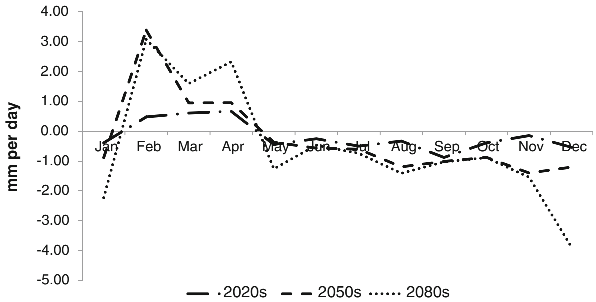

Fig. 7 Absolute differences between projected precipitation and average of the observed base years: HADGEM1

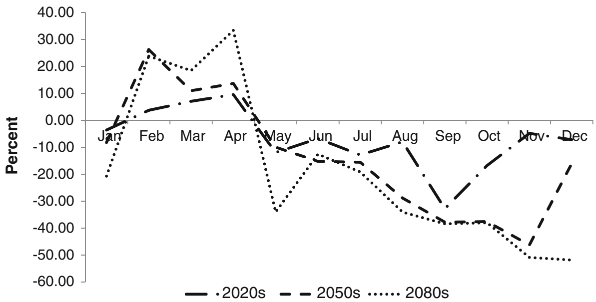

Fig. 8 Percentage differences between projected precipitation and average of the observed base years: HADGEM1

of February, March, and April become increasingly wetter. Figure 7 shows precipitation anomalies (with the observed being the base, 1961–1990, for comparison) for the 2020s, 2050s, and 2080s projections while Fig. 8 shows the percentage change in precipitation between the projected and the average of the observed base years.

Figures 7 and 8 confirm the results in Figs. 4, 5, and 6. Note that some relatively wet months such as December and January are projected to experience a decline in precipitation. On average, for the months of February, March, and April precipitation is projected to increase by 0.6 mm/day (per month) in 2020s, 1.8 mm/day in the 2050s, and 2.3 mm/day in the 2080s. Precipitation, on average, is expected to decline by 0.5 mm/day (per month) in the 2020s, 0.8 mm/day (per month) in the 2050s, and 1.0 mm/day (per month) in the 2050s during the Mauritius drier months

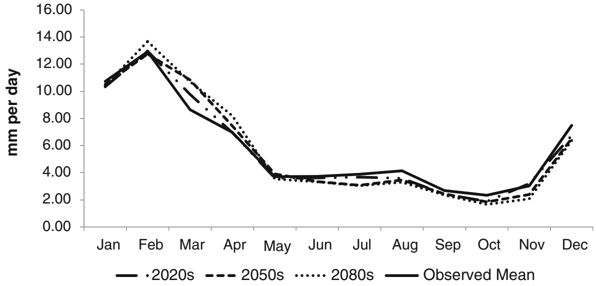

Fig. 9 Observed mean vs. 2020s, 2050s, and 2080s downscaled precipitation for Mauritius: CGCM3 T47

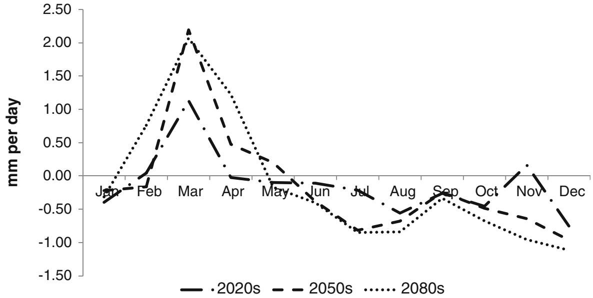

Fig. 10 Absolute differences between projected precipitation (CGCM3 T47) and average of the observed base years

(May to October). In terms of percentages, this means a decrease of 14.9% during the 2020s, 24.2% during the 2050s, and 29.4% during the 2080s compared to 1961–1990 levels for the drier (winter) months. Overall, the Vacoas region is projected to have a decrease in precipitation of 7%, 14%, and 19% for the 2020s, 2050s, and 2080s, respectively.

4.2 CGCM3 T47 Downscaled Results

The downscaled precipitation results for the CGCM3 T47 model are similar to the HADGEM1 model (Fig. 9). Historically wetter months such as February, March, and April are projected to have increased precipitation levels on average in the future. Historically drier months are expected to become drier.

Figures 10 and 11 show the absolute changes and percentage changes, respectively, in projected precipitation from the observed precipitation for each time slice. As in the HADGEM1 projections, the historically wet months of December and January are projected to have decreases in precipitation. Peculiarly, the relatively dry month of November is projected to have an increase in precipitation during the 2020s. For Mauritius drier months (May to October), precipitation is projected to decline by 1.7 mm/day over the course of those 6 months for the 2020s, 2.41 mm/day for the 2050s, and 3.27 mm/day for the 2080s. For the months with the most

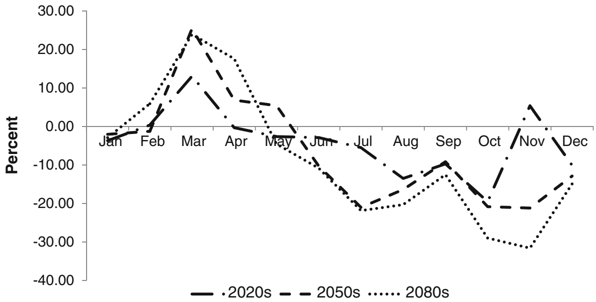

Fig. 11 Percentage differences between projected precipitation (CGCM3 T47) and average of the observed base years

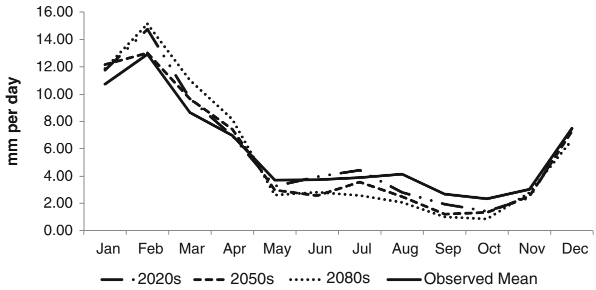

Fig. 12 Observed mean vs. 2020s, 2050s, and 2080s downscaled precipitation for Mauritius: ECHAM 5OM

pronounced increases (February, March, and April), precipitation is projected to increase by about 4% during the 2020s, 10% during the 2050s, and by 16% during the 2080s.

4.3 ECHAM 5OM Results

The downscaled precipitation for the ECHAM 5OM GCM is shown in Fig. 12. We observe similar trends in the ECHAM 5OM projections as in the CGCM3 T47 and HADGEM1 projections. In general, wet months are also projected to become wetter and dry months are projected to become drier. The further into the future, the greater the increase in precipitation during the wet months and the greater the decrease in precipitation during the dry months. The magnitude of the decrease during the dry months is greater in the ECHAM 5OM model than in the other models (except for the 2020s where HADGEM1 showed a larger decline in total precipitation during the drier months (May to October)). However, there is a peculiar feature of the ECHAM 5OM projections. Unlike the projections of the other three GCMs, the months of June and July, which are considered "dry" months, are projected to have increased precipitation during the 2020s. This is more clearly demonstrated in Figs. 13 and 14 which show the absolute and

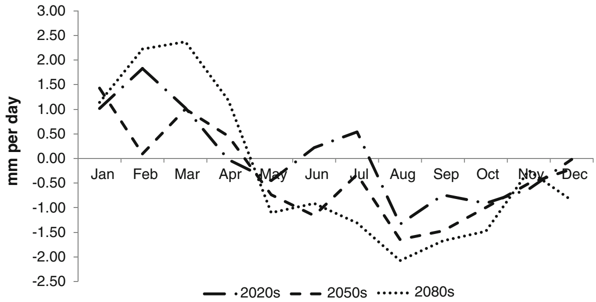

Fig. 13 Absolute differences between projected precipitation (ECHAM 5OM) and average of the observed base years

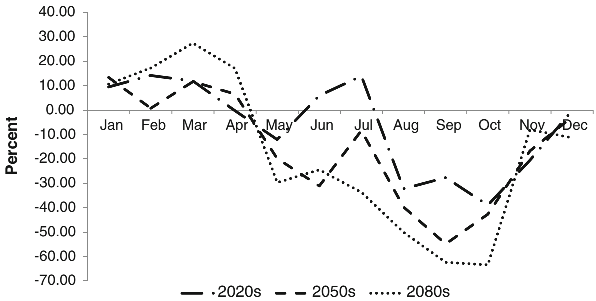

Fig. 14 Percentage differences between projected precipitation (ECHAM 5OM) and average of the observed base years

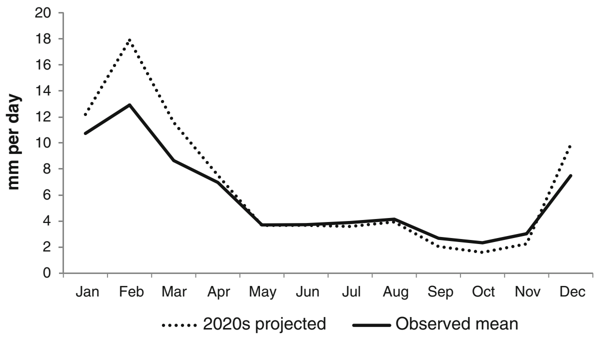

Fig. 15 Observed mean vs. 2020s downscaled precipitation for Mauritius: CSIRO Mk 3.5

percentage differences of the projections from the observed base period. We also observe an increase in precipitation for the relatively wet month of January which we do not observe in the projections of the HADGEM1 and CGCM3 T47 models.

4.4 CSIRO Mk 3.5 Results

Unlike the HADGEM1, CGCM3 T47, and ECHAM 5OM's projections, the CSIRO Mk 3.5's projections indicate an increase in precipitation during the month of December for all three time slices (see Figs. 15, 16, and 17). Most of the trends

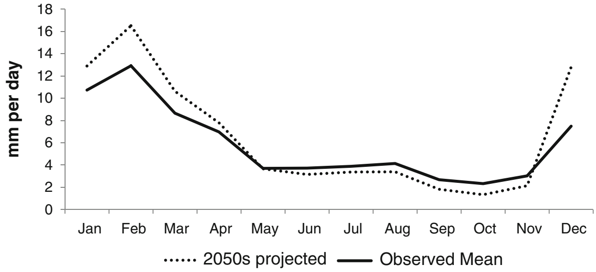

Fig. 16 Observed mean vs. 2050s downscaled precipitation for Mauritius: CSIRO Mk 3.5

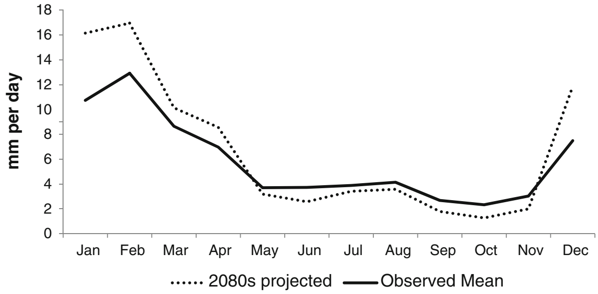

Fig. 17 Observed mean vs. 2080s downscaled precipitation for Mauritius: CSIRO Mk 3.5

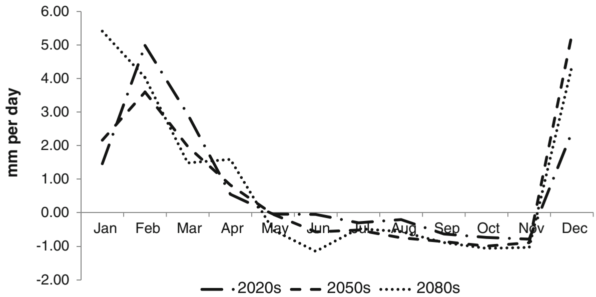

Fig. 18 Absolute differences between projected precipitation (CSIRO Mk 3.5) and average of the observed base years

observed in the HADGEM1, CGCM3 T47, and ECHAM 5OM projections (wet months becoming wetter and dry months becoming drier) are also observed in the CSIRO Mk 3.5 projections. However, the magnitudes of the increase during the wet months are greater in the CSIRO Mk3.5 model projections than the HADGEM1, CGCM3 T47, and ECHAM 5OM model projections (Figs. 18 and 19). This is evident in the total annual precipitation projection amounts. The CSIRO Mk 3.5 projections show an average annual *increase* in total precipitation by 282 mm for the 2020s, 277 mm for the 2050s, and 336 mm for the 2080s. The CGCM3 T47 model shows an average annual *decrease* in total precipitation of 48 mm for the 2020s, 52 mm for the 2050s as well as the 2080s while the HADGEM1 model

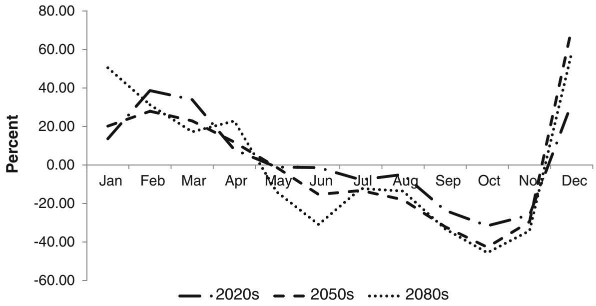

Fig. 19 Percentage differences between projected precipitation (CSIRO Mk 3.5) and average of the observed base years

shows an average annual decrease in total precipitation of 67 mm for the 2020s, 96 mm for the 2050s, and 227 mm for the 2080s. In general, May remains a transitionary month in the CSIRO Mk 3.5 as well as the other three model projections.

4.5 *Comparison of Models*

The summer months of Mauritius last from November to April. In this period the majority of cyclonic activity occurs but it is also the period in which most of the water which serves the inhabitants of Mauritius is collected. Winter months span May to October and are drier. Tables 1 and 2 show how the projected precipitation during the summer (wetter) and winter (drier) months compare with the historical base period, respectively. Table 3 shows the total average annual increase or decrease in precipitation between future projections and the observed baseline period.

The largest increase in precipitation during the summer (wetter) months is projected to occur under the CSIRO Mk 3.5 model for all time slices while the largest decline in precipitation during the winter (drier) months is projected to occur under the ECHAM 5OM for the 2050s and 2080s. The largest decline in precipitation during the drier months is projected to occur under the HADGEM1 model for the 2020s. The HADGEM1 model projects a decrease in precipitation during the wetter months for the 2080s; no other model projects a decline in precipitation during the wetter months for any time slice. During the 2020s, precipitation can increase by as much as 343 mm during the wet season but also a decrease in precipitation of 86 mm can occur during the dry months. Overall, when we average the increases that are projected for all of the GCMs for all time slices we find that the average overall increase in total precipitation (136 mm) during the wetter months is larger than the average overall decreases that are projected to occur (126 mm) during the drier months. However, further into the future the effect of the decrease in precipitation during the drier months outweigh the increases received

Table 1 Selected statistics of projected precipitation compared to the observed precipitation for baseline period (1961–1990): summer (wetter) months only (November to April)

	Average daily difference (absolute) (mm)	Percentage change in daily precipitation (%)	6-month average total change in precipitation (absolute) in (mm)
HADGEM1			
2020s	0.1	7.4	18.8
2050s	0.3	11.4	45.9
2080s	−0.2	−2.6	−39.7
CGCM3 T47			
2020s[a]	0.0	0.3	4.6
2050s	0.1	1.4	21.6
2080s	0.2	2.6	39.7
ECHAM 5OM			
2020s	0.5	6.3	94.8
2050s	0.4	4.7	68.4
2080s	0.9	10.9	163.7
CSIRO Mk 3.5			
2020s	1.9	22.9	343.0
2050s	2.2	26.2	391.8
2080s	2.7	30.3	478.6

[a]The average daily difference is 0.03 mm rounded to the nearest 2 decimal places

Table 2 Selected statistics of projected precipitation compared to the observed precipitation for baseline period (1961–1990): winter (drier) months only (May to October)

	Average daily difference (absolute) (mm)	Percentage change in daily precipitation	6-month average total change in precipitation (absolute) in (mm)
HADGEM1			
2020s	−0.5	−13.7	−85.7
2050s	−0.8	−22.6	−142.0
2080s	−1.0	−29.4	−187.1
CGCM3 T47			
2020s	−0.3	−8.3	−52.2
2050s	−0.4	−11.8	−74.1
2080s	−0.6	−17.2	−109.3
ECHAM 5OM			
2020s	−0.5	−13.1	−82.3
2050s	−1.1	−30.8	−193.7
2080s	−1.5	−42.6	−270.9
CSIRO Mk 3.5			
2020s	−0.3	−9.6	−60.3
2050s	−0.6	−18.2	−114.4
2080s	−0.8	−24.0	−142.2

Table 3 Projected change in total annual precipitation relative to the 1961–1990 period

	Average absolute difference in total annual precipitation (mm)
HADGEM1	
2020s	−66.9
2050s	−96.1
2080s	−226.8
CGCM3 T47	
2020s	−47.6
2050s	−52.5
2080s	−69.6
ECHAM 5OM	
2020s	12.4
2050s	−123.7
2080s	−107.2
CSIRO Mk 3.5	
2020s	282.7
2050s	277.4
2080s	336.4

Table 4 Projected change in precipitation (in %) relative to 1961–1990 baseline period: down-scaled GCM and IPCC [1] projections

	Average percentage change in total annual precipitation		
	2020s	2050s	2080s
HADGEM1	−3.2	−4.5	−10.6
CGCM3 T47	−2.2	−2.5	−3.3
ECHAM 5OM	0.6	−5.8	−5.0
CSIRO Mk 3.5	13.3	13.1	15.8
IPCC (2007)	−5.4 to +6.0	−6.9 to +12.4	−9.8 to +14.7

during the wetter months. Indeed, the average increase in precipitation for all GCM projections during the 2080s is 161 mm while the average decline in precipitation is 177 mm for that time slice. Three out of the four projections for the 2080s time slice show a larger average annual decline in precipitation during the drier months than the average annual increase during the wetter months. Table 4 compares down-scaled projections with IPCC (2007) projections for the Indian Ocean region.

Most of our projections are in line with the IPCC [1] results. The exception is the CSIRO Mk 3.5 model which shows a slightly higher increase in precipitation levels than the IPCC [1] projections for 2050s and 2080s. Note that for the Indian Ocean region, precipitation is projected to increase or decrease in the future. Our down-scaled projections also reflect this feature.

5 Conclusion

Like many small island states, Mauritius faces the problem of sea level rise as a result of global climate change. This is particularly serious because 90% of the population lives within 1 km of the coast [7]. According to available literature, climate change is likely to bring more intense cyclones, with the possibility of severe damage to infrastructure and possible loss of life. Our research discussed in this chapter quantifies in detail possible future changes in the precipitation patterns and their likely climate change impacts in the Vacoas-Phoenix region of Mauritius.

Our projections for the future indicate that precipitation will increase during the historically wetter months and decrease for the historically drier months. Although precipitation is likely to increase in the wetter months, it does not compensate for the decrease in precipitation during the drier months because of the inability to store the "extra" precipitation. The more grave concern is a situation where there is a decline in mean annual precipitation which three of our GCMs, appropriately downscaled, seem to project for the future. For the earliest time slice which is the 2020s, all four models project a decline in average daily precipitation from 8% to 14% compared to the base period (1961–1990) for the drier months. Three out of the four projections for the 2080s time slice also show a larger average annual decline in precipitation during the drier months than the average annual increase during the wetter months and hence a net annual decline in precipitation. Thus this research quantifies by how much total annual precipitation is likely to decline.

Since the Vacoas region has been increasingly reliant on tourism as a source of employment, the influx of tourists and the likely increase in demand for water as a result would put a strain on the available water resources. Furthermore, due to the lack of financial resources, Mauritius, like many SIDS, may not be able to expand current storage facilities in order to adapt to the expected impacts of future climate change. Hence, innovative ways of managing the water resources in the region will be critical not only for the water needs of the local population but also for the growing tourism-based economy.

References

1. IPCC (2007) Climate change 2007: synthesis report. In: Core Writing Team, Pachauri RK, Reisinger A (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change, IPCC, Geneva, p 104
2. Mimura N, Nurse L, McLean RF, Agard J, Briguglio L, Lefale P et al (2007) Small islands. climate change 2007: impacts, adaptation and vulnerability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, pp 687–716

3. IPCC (2001) Climate change 2001: Working Group II: impacts, adaptation and vulnerability. Small Island States. http://www.grida.no/publications/other/ipcc_tar/. Accessed 1 December 2012
4. IPCC (2010) Workshop report of the intergovernmental panel on climate change workshop on sea level rise and ice sheet instabilities. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen S, Midgley PM (eds) IPCC Working Group I Technical Support Unit, University of Bern, Bern, p 227
5. World Meteorological Organization (2004). Saving paradise – ensuring sustainable development. WMO. No. 973, Geneva, Switzerland
6. Mauritius Meteorological Services (2012) Climate change: climate change and sea level rise in Mauritius. http://metservice.intnet.mu/?cat=46. Accessed 1 December 2012
7. International Council for Local Environmental Initiative (2011) Sub-Saharan African Cities: a Five-City network to pioneer climate adaptation through participatory research and local action: Port Louis Baseline Study. ICLEI – Local Governments for Sustainability, Africa
8. Mauritius Chamber of Commerce and Industry (2012) online bulletin dated June 2012. http://www.mcci.org/economy_figures.aspx#NationalAccounts Accessed 21 December 2012
9. Google Maps (2012) [Mauritius][Street view] http://maps.google.ca/maps?hl=en&qscrl=1&rlz=1T4TSCA_enCA447CA447&bpcl=39468505&ion=1&bav=on.2,or.r_gc.r_pw.r_qf.&biw=1366&bih=566&wrapid=tlif135468119329210&q=mauritius&um=1&ie=UTF-8&hq=&hnear=0x217c504df94474c9:0x4203d9c2116bd031,Mauritius&gl=ca&sa=X&ei=MMq-UOOLBuGkyQGOwYCgBg&ved=0CJcBELYD. Accessed 1 December 2012
10. Johns TC, Durman CF, Banks HT, Roberts MJ, McLaren AJ, Ridley JK et al (2006) The new Hadley Centre climate model HadGEM1: evaluation of coupled simulations. J Clim 19:1327–1353
11. Martin GM, Ringer MA, Pope VD, Jones A, Dearden C, Hinton TJ (2006) The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model, HadGEM1. Part 1: model description and global climatology. J Clim 19:1274–1301
12. Ringer MA, Martin GM, Greeves CZ, Hinton TJ, James PM, Pope VD et al (2006) The physical properties of the atmosphere in the new Hadley Centre Global Environmental Model, HadGEM1. Part 2: aspects of variability and regional climate. J Clim 19:1302–1326
13. McFarlane NA, Scinocca JF, Lazare M, Harvey R, Verseghy D, Li J (2005) The CCCma third generation atmospheric general circulation model. Centre for Climate Modelling and Analysis. Internal Rep p 25
14. Scinocca JF, McFarlane NA, Lazare M, Li J, Plummer D (2008) The CCCma third generation AGCM and its extension into the middle atmosphere. Atmos Chem Phys 8:7055–7074
15. Roeckner E, Bäuml G, Bonaventura L, Brokopf R, Esch M, Giorgetta MS et al (2003) The atmospheric general circulation model ECHAM 5. PART I: Model description. Max Planck Institute for Meteorology. MPI-Report No. 349
16. Hanke JE, Wichern DW (2005) Business forecasting, 8th edn. Pearson Practice Hall, New Jersey
17. Gordon H, O'Farrell S, Collier M, Dix M, Rotstayn L, Kowalczyk E et al (2010) The CSIRO Mk3.5 Climate Model. The Centre for Australian Weather and Climate Research Technical Report. No. 021
18. Box G, Jenkins G (1970) Time series analysis: forecasting and control. Holden-Day, San Francisco

Part II
Potential Impacts of Climate Change

Climate Change Impacts on Water Resources in SemiArid Regions: Case Study of Aswan High Dam Reservoir

Mohamed Elshemy

Abstract This chapter presents an introduction to the global climate change (GCC) phenomenon. The historical and future impacts of climate change on different characteristics of international water resources were reviewed. The expected effects of climate change on Egyptian water resources, as examples of semiarid region water resources, were addressed. The southern part of Aswan High Dam Reservoir, Lake Nubia, was chosen to quantify the potential influence that GCC may have on its hydrodynamic and water quality characteristics. These impacts have been investigated using a proposed hydrodynamic and water quality model of Lake Nubia, for the twenty-first century – with two emission scenarios, including the average of 11 global climate models outputs. To estimate the future initial conditions of the proposed model, a theoretical process algorithm was simplified, developed, and calibrated. The investigated hydrodynamic characteristics were water surface levels, evaporation water losses, and reservoir thermal structure. While the studied water quality parameters of the reservoir were pH, dissolved oxygen, chlorophyll-*a*, ortho-phosphate, nitrate–nitrite, ammonium, total dissolved solids, total suspended solids. In addition, a sensitivity analysis for the future climate estimates was conducted. The results show that there will be significant impacts of the climate change on the examined hydrodynamic and water quality characteristics of Lake Nubia.

Keywords Aswan High Dam Reservoir, Climate change, Lake Nubia, Semiarid regions, Water quality model

M. Elshemy (✉)
Department of Irrigation and Hydraulic Engineering, Tanta University, Tanta, Egypt
e-mail: m_elshemy@yahoo.com; m.elshemy@f-eng.tanta.edu.eg

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 69–98, DOI 10.1007/698_2013_223,

Contents

1 Introduction

Climate change is a "normal" climatic phenomenon; the climate has always been changing throughout the history of the Earth. Natural changes in climatic conditions have resulted in Ice Ages and relatively warm periods in temperate regions while wet periods have intermitted with dry periods in Africa [1]. Climate change, since the last century, however has been accelerated due to the increase in greenhouse gases related to human activities [2].

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to assess the environmental and socioeconomic implications of climate change and the possible response options available to governments. IPCC has released four assessment reports in 1990, 1995, 2001, and 2007.

The latest IPCC Assessment Report (IPCC AR4) [3, 4] stated that Earth's average temperature is unequivocally warming, 11 of the past 12 years have been the warmest on record since 1850, which is when global instrumental record-keeping began. The report documented that anthropogenic factors (due to human activity) are responsible for most of the current global warming. The primary anthropogenic source is the emission of greenhouse gases such as carbon dioxide, which is mainly produced by the burning of fossil fuels.

Although scientists are confident about the fact of global warming and climate change due to human activities, substantial uncertainty remains about just how large the warming will be and what will be the patterns of change in different parts of the world [5]. Different global climate models or general circulation models (GCMs) are designed by various groups of scientists and used to predict the impact of enhanced greenhouse effect on climate change, by using different emission scenarios. A wide range of emission scenarios was developed by the IPCC in a Special Report on Emission Scenarios (SRES), which is available at its web site [6]. The main scenarios storylines are as follows [7]:

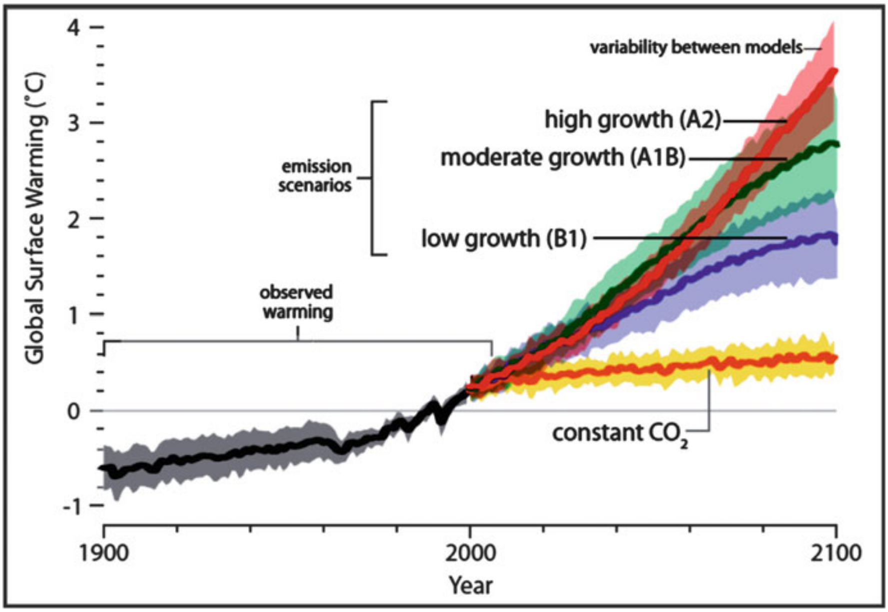

Fig. 1 Warming projections to the year 2100 [8]

- A1 Storyline describes a world of rapid economic growth and rapid introduction of new and more efficient technology.
- A2 Storyline describes a very heterogeneous world with an emphasis on family values and local traditions.
- B1 Storyline describes a world of "dematerialization" and introduction of clean technologies.
- B2 Storyline describes a world with an emphasis on local solutions to economic and environmental sustainability.

IPCC projects that global average temperatures in 2100 will be between 1.8°C and 4.0°C higher than the 1980–2000 average (best estimate, likely range 1.1–6.4°C). Sea levels are projected to rise 0.18–0.59 m by 2100. More frequent and intense extreme weather events (including drought and flooding) are also expected. Figure 1 shows temperature projections to the year 2100, based on a range of emission scenarios and global climate models. The line of "Constant CO_2" projects global temperatures with greenhouse gas concentrations stabilized at year 2000 levels.

2 Climate Change Impacts on Water Resources

The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level, and precipitation variability (very high confidence). Semiarid and arid areas are particularly exposed to the impacts of climate change on freshwater (high confidence) [9]. Observations indicate that lakes and rivers around the world are warming, with effects on thermal structure and lake chemistry that in turn affect abundance and productivity, community composition, phenology, distribution and migration [10]. Higher water temperatures, increased precipitation intensity, and longer periods of low flows are projected to exacerbate many forms of water pollution, including sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt, and thermal pollution. This will promote algal blooms, and increase the bacterial and fungal content. This will, in turn, impact ecosystems, human health, and the reliability and operating costs of water systems [11]. European Environment Agency (EEA) [12] has listed some expected water quality problems for water resources because of temperature changes as follows:

- Reduced oxygen content. Increases in water temperature in streams and rivers reduce oxygen content and increase biological respiration rates and thus may result in lower dissolved oxygen concentrations, particularly in summer low-flow periods.
- Alterations to habitats and distribution of aquatic organisms.
- Alterations to thermal stratification and mixing of water in lakes.
- Changed nutrient cycling in aquatic systems and algal blooms.
- Increase of bacterial populations that control nitrogen mineralization and nitrification processes in the soils.

Detailed expected climate change impacts on water resources have been discussed in numerous studies [9, 11, 13–19]. State-of-the-art research into the implications of climatic change for the hydrologic cycle and for water resources has been reviewed in some other publications [11, 19–23].

GCMs and hydrological models have been used to predict future hydrological characteristics of rivers basins [13, 24–26]. For example, the effects of climate change on the discharge regime in different parts of the Rhine basin were calculated using the results of UKHI and XCCC GCM-experiments [26]. All models indicate the same trends in the changes: higher winter discharge as a result of intensified snow-melt and increased winter precipitation, and lower summer discharge due to the reduced winter snow storage and an increase of evapotranspiration.

Hondozo and Stefan [27] addressed three approaches that can be used to investigate climate change impacts on lakes water temperature: examination of long-term records; comparing individual warm and cold or wet and dry years if the records are short but detailed; or using numerical simulation models to calculate heat transfer from the atmosphere to the lake water columns.

Studies of climate change impacts based on past long-term records have been addressed in the literature [28–36]. In 2000, the effects of past long-term, 1979–1996, climate change on the water quality of Lake Kasumigaura, Japan, were investigated [29]. The authors developed a statistical regression relationship between the past meteorological conditions and lake water quality parameters. They reported that the deterioration of lake water quality, such as increases in COD and decreases in transparency, was quantitatively assessed as corresponding to an increase in air temperature. In addition, they found that higher precipitation led to high nitrogen concentrations on a monthly basis, as well as on a yearly basis. O'Reilly et al. [33] have investigated the effect of past climate change on water temperature and the water column stability, which is defined as the work required to mix the water column to uniform density, of Lake Tanganyika, Africa. The authors stated that in parallel with regional warming patterns since the beginning of the twentieth century, a rise in surface-water temperature has increased the stability of the water column. A regional decrease in wind velocity has contributed to reduced mixing, decreasing deep-water nutrient upwelling and entrainment into surface waters. In 2008, the effects of past (1969–2002) and future (2000–2040) climate change on the physical characteristics of Lake Tahoe, California – Nevada, USA, were investigated [35]. For future climate change impact study, one emission scenario (A2) for one GCM (GFDL) and two models (watershed model and hydrodynamic and water quality model) were used. The past records show that Lake Tahoe has become warmer and more stable, while the predicted trends show that the lake continues to become warmer and more stable, and mixing is reduced. The authors discussed the possible changes in water quality because of global warming, and expect that if the warming trend continues, Lake Tahoe will be permanently stratified, resulting in low DO concentrations in the hypolimnion.

Climate change impacts on the hydrodynamic characteristics of lakes have been investigated in numerous publications [27, 30, 35, 37–44]. Hondzo and Stefan (1993) used a validated, one-dimensional, unsteady lake water quality model to simulate 27 classes of lakes in Minnesota, USA, for past daily time base (1955–1979) and future climate scenario [27]. One emission scenario and double CO_2 for one GCM (GISS) were used in the study. The simulations predict that epilimnetic temperatures will be higher, hypolimnetic temperatures in seasonally stratified dimictic lakes will be largely unchanged or even lower than at present, evaporative water loss will be increased by as much as 300 mm for the season, onset of stratification will occur earlier and overturn later in the season, and overall lake stability will become greater in spring and summer. Similar studies were conducted later for the same 27 classes of lakes with different water quality models and GCMs [39, 44]. In 1998, climate change effects on the hydrodynamic characteristics of Lake Qinghai, Qinghai-Tibet Plateau, China, were investigated [42]. Catchment model, lake thermodynamic model, and lake water balance model, and results of four GCMs (GFDL, GISS, OSU, and UKMO) for doubling CO_2 were used in the study. The results show that the total runoff in the lake and evaporation will, in most cases, increase as conditions become warmer and wetter. The lake level changes would remain uncertain because the effects of an increase in precipitation are countered by the rise of temperature. Another study examined the impact of future climate change on the thermal structure of Amistad Reservoir, Texas, USA [38]. In the study, CE-QUAL-W2, the hydrodynamic and water quality model, and the result of one GCM (CCC GCM) for doubling CO_2 were used. The results show a strong impact on both surface and bottom water temperature in the reservoir.

Up to now, the effects of climate change on the water quality of water resources are reported in a few publications [45–52]. One of the first trials to study the impact of climate change on fish habitat in Douglas Reservoir, Tennessee (USA), was done in 1992 [45]. The authors used the results of three GCMs (two grid cells for each) for double CO_2 and a water quality model. Several assumptions were made in order to estimate most of the required input data for the water quality model. Daily reservoir volumes with optimal, suboptimal, and unsuitable temperature and dissolved oxygen were predicted for one annual cycle. The authors conclude that the reservoir model was found to be a promising tool for examining potential climate change impacts. However, some of the assumptions required to apply GCM output to the reservoir model illustrate the problems of using large-scale grid cell output to assess small-scale impacts.

In 1996, a new water temperature-ecological model was applied to Lake Yunoko, Japan [50]. The calibrated model was used to assess the effects of global warming by increasing air temperature to 24°C. Significant impacts on thermal, chemical, and biological characteristics of the lake were found. In 1998, a new mathematical eutrophication model to simulate phytoplankton growth rate and dissolved oxygen for Suwa Lake, Japan, was developed [49]. The authors assessed the impact of future climate change on phytoplankton growth rate, a downscaling method was applied to (HadCM2SUL) GCM for (2080–2099).

In 2004, a study of three parts [46–48] was done to assess the impact of climate change on fish habitat, which is strongly constrained by water temperature and available dissolved oxygen (DO). The authors used the same water quality model, emission scenario, and GCM for the same 27 classes of lakes of that study of Fang and Stefan [39]. The vertical DO profiles in the lake are computed from a balance between oxygen sources (reaeration and photosynthesis) and oxygen sinks (sedimentary oxygen demand, biochemical oxygen demand, and plant respiration). The authors reported that errors between simulated and measured DO concentrations are in part caused by using constant biochemical oxygen demand (BOD) and sediment oxygen demand (SOD) values regardless of season and location, although they depend on the trophic status and lake depth in the model.

In 2006, the climate warming impact on phosphorus dynamics in lakes was investigated [52]. A physical lake model and a mechanistic phosphorus model were combined with two temperature scenarios generated by a regional climate model (RCM) in three sites in central Sweden – Lake Erken and two basins of Lake Mälaren. The model results indicated that lakes may respond very differently to climate change depending on their physical characteristics, especially water residence time which is about 7 years for Lake Erken and 0.07 and 0.5 for the other two basins of Lake Mälaren. In Lake Erken the concentration of epilimnetic-dissolved phosphorus is almost doubled in spring and autumn in the warmest climate scenario, since the lake is mostly phosphorus limited, this means that the potential for phytoplankton production is almost doubled. In other eutrophic lakes with long water residence times, eutrophication problems may become serious in the future.

The long-term effect of global warming on environmental variables, such as water temperature, dissolved oxygen and nutrients as well as aquatic ecosystems, was evaluated by Komatsu et al. [51]. The developed watershed runoff model and reservoir water quality model with meteorological input calculated by a GCM A2 scenario was applied to Shimajigawa Reservoir, Japan. The results were shown to cause more trophic lake conditions, further promoting algal growth and changing the aquatic ecosystems.

3 Climate Change Effects on Egyptian Water Resources

It is expected that Egypt will be strongly threatened by the hydrological impacts of global climate change (GCC). This is because Egypt lies within a region where GCC-related effects will be most damaging, and the ability to respond to harmful change is extremely limited [53]. The major, and sometimes the only, viable option to cope with climate change is adaptation. The adaptation strategies for Egypt developed under the National Water Resources Plan (NWRP) are categorized into three main directions: optimal use of available resources, development of new resources, and water quality preservation/improvement [54]. The first and second Egyptian communications reports [55, 56] which were prepared by the Egyptian Environmental Affairs Agency (EEAA) for submission to the United Nations Framework Convention on Climate Change (UNFCCC) reported the following facts: Egypt is one of the most vulnerable countries to the potential impacts and risks of climate change, even though it produces less than 1% of the world total emissions of GHG, because of vulnerability in all sectors of development and a low resilience of the majority of stakeholders. The sectors of water resources, agricultural resources and food security, coastal resources, tourism, and health are highly vulnerable with serious socioeconomic implications.

More than 95% of the water budget of Egypt is received from the River Nile which originates outside Egypt. Numerous studies show that River Nile is very sensitive to temperature and precipitation changes mainly because of its low runoff/rainfall ratio (4%) [57]. Therefore, it is of prime importance for Egypt to assess the hydrological impacts of climate change on the River Nile [54]. The implications of climate fluctuations for water management with emphasis on the Nile were considered in some publications [58, 59]. Several studies have investigated the potential impact of climate change on the River Nile and associated impacts on the Egyptian economy [60–64]. Moreover, the impacts of climate change on the Egyptian agriculture sector have been detailed in numerous publications [65–68].

Gleick [69] used a model based on annual water balance to study the vulnerability of runoff in Nile Basin to climate change. The model was applied to three subbasins of the Nile Basin: the Upper White Nile (Sobat), Blue Nile, and Atbara. The model produced a 50% reduction in runoff in the Blue Nile catchment due to an assumed 20% decrease in precipitation.

Riebsame et al. [57] applied three GCMs, Goddard Institute of Space Science (GISS), Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University, and the United Kingdom Meteorological Office (UKMO), for doubled CO_2 levels and a hydrological model to generate multi-year time series of monthly stream-flow at Aswan. The results showed that the average annual Nile flow at Aswan (84 BCM) will increase by 30% for GISS GCM scenario, while the flow will decrease for GFDL GCM and UKMO GCM scenarios by 77% and 12%, respectively.

Conway and Hulme [70] used hydrologic models of the Blue Nile and Lake Victoria subbasins to assess the magnitude of potential impacts of climate change on Main Nile discharge. The models were calibrated to simulate historical runoff and then used temperature and precipitation changes predicted from three GCMs climate scenarios; a “wet” case (GISS GCM), “dry” case (GFDL GCM), and composite case (a weighted mean of seven equilibrium GCMs). The following changes in Egypt’s allocation of Nile water (estimated as about 55 km^3) were obtained due to 1°C temperature increase: +0.8, −4.9, and +8.4 km^3 with both temperature and precipitation changes applied from the composite, GFDL and GISS GCM scenarios, respectively.

In 1996, the impacts of GCC on the water resources of the River Nile Basin were evaluated using four climate change scenarios (baseline, GISS, GFDL, and UKMO) [71]. The authors concluded that the complete impact of climatic change on the Nile cannot be fully predicted with confidence, because some models forecast increased flows, while others project significant decreases. The River Nile flows under GCMs scenarios were as follows: 88% (UKMO GCM), 130% (GISS GCM), and 23% (GFDL GCM), relative to the average annual Nile flow at Aswan (84 BCM). The authors concluded that it is possible that the effects of climatic fluctuations on the River Nile would be severe.

The Organization for Economic Cooperation and Development (OECD) has published a study which reports significant risks of climate change in Egypt [72]. Changes in average temperature and precipitation over Egypt were assessed based on the results of eight GCMs for IPCC B2 emission scenario. The study also examined the climate models projections for the source waters of the Nile, in the Ethiopian highlands and equatorial lakes region. All models expect temperature to rise, while for rainfall, the magnitude and signal of change substantially vary across the models.

Conway [73] documented studies conducted since the early 1990s that highlight the inharmonious of climate model scenarios of rainfall over the Nile Basin, while climate scenarios of rising temperatures are more consistent and could lead to large increases in the evaporation because of the large expanses of open water and irrigated agriculture in the basin.

Mohamed et al. [74] applied a RCM to the Nile Basin. The model was customized to simulate the regional climate (tropical, semiarid, and arid climates) of Nile Basin. The exercise concentrated on reproducing the regional water cycle as accurately as possible. Observations on runoff, precipitation, evaporation, and radiation were used to evaluate the model results at the subbasin level (White Nile, Blue Nile, Atbara, and the Main Nile). Subsequently, the model was used to compute the regional water cycle over the Nile Basin. The results showed that the model reproduced runoff reasonably well over the Blue Nile and Atbara subbasins, while it overestimated the White Nile runoff. Except for the period March to June over the White Nile, the model simulated the precipitation well over the four subbasins. The evaporation over the Sudd wetland could be accurately simulated during the rainy season, while it was overestimated during the dry months.

Soliman et al. [75] calibrated another RCM by using different observed data for Blue Nile and Sobat River subbasins. The results of this RCM were used to simulate the runoff pattern by using a hydrological model which is connected to the regional climate mode.

Sayed [76] has reported some needed research which help in studying climate change risks on the Nile Basin such as calibration and validation of a RCM to test the impacts of extreme scenarios on the spatial and temporal distribution of rainfall over the Nile Basin.

Attia [54] has assessed the Egyptian water resources vulnerability under climate change by presenting the results of climatic scenarios based on three GCMs (CGCM2, ECHAM4, and HadCM3) for two emission scenarios (A2 and B2). These three models were selected based on the Lake Nasser Flood and Drought Control project (LNDFC) which constructed climatic scenarios based on the results from 11 GCMs for the B2 emission scenario. These scenarios were taken from the OECD study [72], which presented mean annual and seasonal (winter and summer) temperature and precipitation changes over the source areas of the Nile basin. The study used these changes to estimate the impacts of climate change on the inflows to Lake Nasser showing a wide range of changes for 2030, 2050, and 2100. The author concluded that the assessment of impact of climatic change on the Nile is strongly dependent on the choice of the climate scenario and the underlying GCM experiment.

In 2009, the impacts of climate change on both hydrology and water resources operations of Blue Nile River were analyzed using the outcomes of six different GCMs for the 2050s [77]. The changes in outflows from two proposed dams to downstream countries were also estimated. Given the uncertainty of different GCMs, the simulation results of the weighted scenario suggested small increases in hydrologic variables (precipitation, temperature, potential evapotranspiration, and runoff) across the study area.

The outputs of 17 GCMs for A1B emission scenario, included in the IPCC AR4, were downscaled for the 2081–2098 period for the upper Blue Nile Basin [78]. These were used to drive a fine-scale hydrological model of the Nile Basin to assess their impacts on the flows of the upper Blue Nile at Diem, which accounts for about 60% of the mean annual discharge of the Nile at Dongola. The ensemble mean annual flow at Diem will be reduced by 15% compared to the baseline. However, the very high sensitivity of flow to rainfall makes such a number highly uncertain.

Elshamy et al. [79] analyzed the change in Nile flows at Dongola using the results of three GCMs (CGCM2, ECHAM4, and HadCM3) for two emission scenarios (A2 and B2). The GCMs results were downscaled and bias corrected by using a statistical downscaling model. A fine-scale hydrological model of the Nile Basin was used to simulate the inflow. The results show that the ECHAM4 predicts a steady increase in Nile flows in the future. CGCM2 underestimates the flow compared to the mean observed flow during the base period (1992–2001). The HadCM3 shows a slight trend of increase compared to the flood season flows and a slight trend of increase compared to the flow during the base period.

A simplified model was used to simulate two different future scenarios to study the effect of the water temperature rise (in the Rosetta branch of River Nile) on the DO concentrations [80]. The effect of climate change has been investigated by assuming air water temperature rise by 1.5°C and 3°C and another reduction factor has been applied to have the water temperature rises according to the air temperature increase. The results indicated that global warming might increase the stress on Rosetta branch and decline its water quality. If this effect was accompanied by flow reduction, deterioration in the quality status of the branch might be severe.

Radwan [80] evaluated the evaporation losses from Aswan High Dam Reservoir (AHDR) at year 2050 due to the expected climatic changes. The author used two different meteorological data sets to obtain the different meteorological parameters trend. He applied seven methods to calculate evaporation losses for the present and in the future. Results show that the evaporation losses from AHDR will be increased by a very negligible amount.

Beyene et al. [81] assessed the potential impacts of climate change on the hydrology of the River Nile Basin for three periods in the twenty-first century: period I (2010–2039); period II (2040–2069); and period III (2070–2099). The authors used the results of 11 GCMs for 2 global emissions scenarios (A2 and B1), archived in the 2007 IPCC AR4. The archived results were bias corrected, and spatially and temporally downscaled. These results were used as the input data of a macroscale hydrological model to predict the river inflow. The simulations show that, averaged over all 11 GCMs, the River Nile is expected to experience increase in stream-flow early in the study period (2010–2039), due to generally increased precipitation. Streamflow is expected to decline during mid- (2040–2069) and late (2070–2099) part of the century as a result of both precipitation declines and increased evaporative demand. The predicted multi-model average stream-flows at AHDR as a percentage of historical (1950–1999) annual average are 111 (114), 92 (93), and 84 (87) for A2 (B1) global emissions scenarios. Implications of these stream-flow changes on the water resources of the River Nile Basin were analyzed by quantifying the annual hydropower production and irrigation water release at AHDR.

4 Case Study: Aswan High Dam Reservoir

Egypt is extremely dependent on the River Nile, the country hardly has any other fresh water resources [82]. Full control of the Nile water discharge was achieved in the 1970s after the construction of the Aswan High Dam (AHD). As a result, the AHD Reservoir was formed. It is considered as one of the largest man-made lakes in the world, with a capacity of about 162 BCM at a water level of 180 m AMSL at the dam site. It is located at the border between Egypt and Sudan between the latitudes 23°58′ and 20°27′N, and the longitudes 30°35′ and 33°15′E, as shown in Fig. 2. The current length of the submerged area is about 500 km, of which 350 km are within the Egyptian territory and is known as Lake Nasser. The 150 km stretch

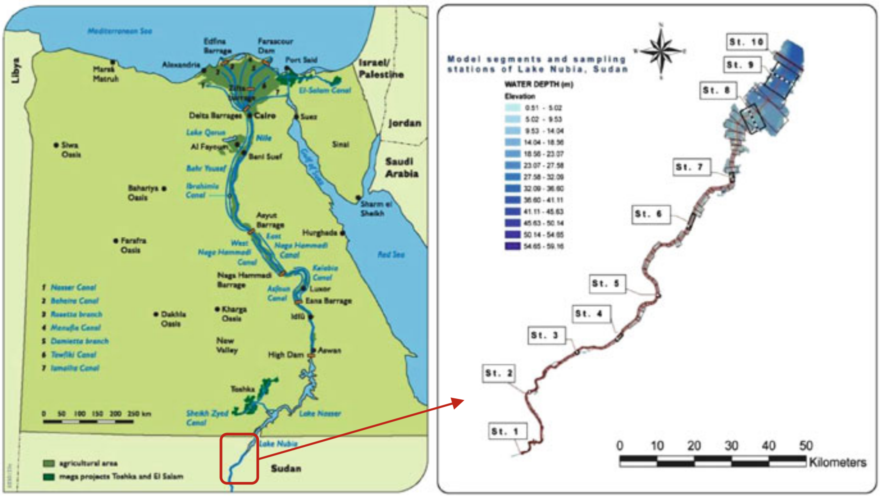

Fig. 2 Location map of Lake Nubia [82], and its sampling stations

which lies in the northern part of Sudan is known as Lake Nubia. The climate change impacts on the hydrodynamic and water quality characteristics of the southern part of AHD Reservoir (Lake Nubia) were investigated in this work.

4.1 *Study Area*

The River Nile is the sole inflow source of Lake Nubia. Lake Nubia can be divided into two sections: the riverine section and the semi-riverine section [83]. The riverine section, with all-year riverine characteristics, comprising the southern part of the lake, from the southern end to Daweishat (St. 5), as shown in Fig. 2. The semi-riverine section, with riverine characteristics during the flood season (from the second half of July to November) and lacustrine characteristics during the rest of the year, covers the northern part of the lake extending from Daweishat. The study area has a desert climate. This area receives virtually no rainfall, except for occasional thunder storms which may sporadically penetrate the area in winter roughly once in every 10 years [83].

4.2 *Methodology*

In order to investigate the impact of future climate change scenarios on the hydrodynamic and water quality characteristics of Lake Nubia, projected changes in climate conditions and a developed hydrodynamic and water quality model for

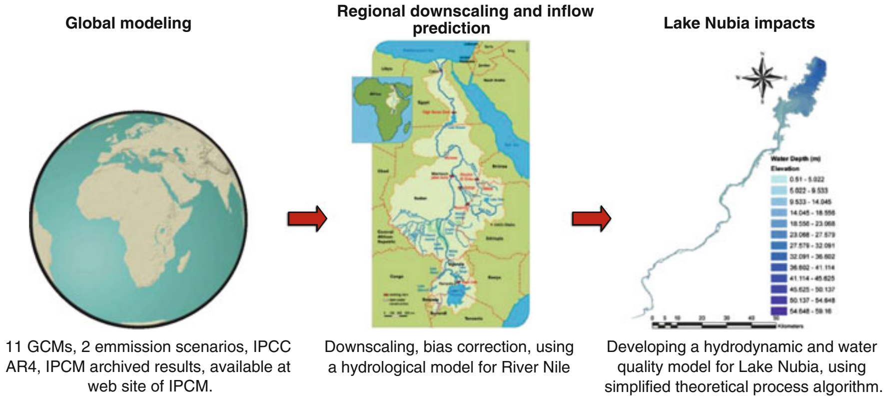

Fig. 3 Approach for analyzing potential impacts of climate change on Lake Nubia

Lake Nubia are required. The projected climate conditions are available from Beyene et al. [81] (see Sect. 4.2.2). A hydrodynamic and water quality model of Lake Nubia was developed by Elshemy et al. [84], see Sect. 4.2.1. Moreover, a simplified theoretical process algorithm is developed to estimate the future dissolved oxygen initial conditions, refer to Sect. 4.2.4. Figure 3 shows a summary of research approach.

4.2.1 Lake Nubia Hydrodynamic and Water Quality Model

Elshemy et al. [84] have developed a two-dimensional (laterally averaged) hydrodynamic and water quality model for Lake Nubia. The developed model was based on a two-dimensional hydrodynamic and water quality modeling system (code), CE-QUAL-W2. This code contains one module, which models both hydrodynamics and water quality. The model can compute water surface elevation, horizontal and vertical velocities, water temperature, and 28 other water quality parameters [85].

The basic input data for CE-QUAL-W2 include reservoir topography (bathymetry), stream-flow, temperature, water quality records as well as meteorological information. The bathymetry of Lake Nubia was modeled by establishing a finite difference grid consisting of three main branches with 202 segments along a longitudinal axis and 27 vertical layers of 2 m depth, as shown in Fig. 4. A specific width was assigned to each cell of the model grid. The inflow data are supplied from a gauging station at the upstream end of the reservoir, St. 1, as shown in Fig. 2. All inflows and reservoir surface elevations were specified as daily average values. The meteorological data were obtained for the nearby local meteorological station from the Internet (website of "Weather Underground" [86]). The recorded data are available for every 6 h.

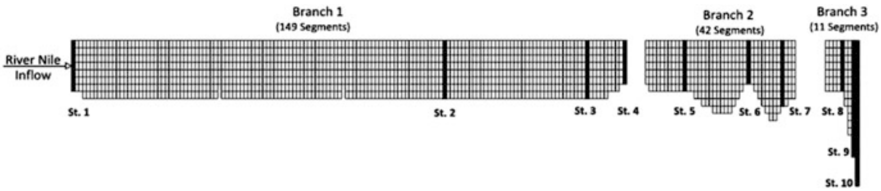

Fig. 4 The finite difference representation for the hydrodynamic model of Lake Nubia

In-reservoir temperature profiles were measured at ten stations (St. 1–10) positioned along the longitudinal axis of Lake Nubia, as seen in Fig. 2. The water samples were collected from the surface and at 25%, 50%, 65%, and 80% depth, where the total depth of Lake Nubia ranges from 3 to 24 m. The field data in January 2006 and in February 2007 were used to calibrate and verify the model, respectively. These field records were collected by the Nile Research Institute (NRI), National Research Center (NRC), Egypt.

Two statistical parameters were used to compare simulated and in-reservoir observations, the absolute mean error (AME) and the root mean square error (RMS) [87].

4.2.2 Climate Change Estimates

To investigate the impact of future climate change scenarios on the hydrodynamic and water quality characteristics of Lake Nubia, projected changes in climate conditions are required. These conditions were obtained from Beyene et al. [81]. The authors assessed the potential impacts of climate change on the hydrology of the River Nile Basin for three periods in the twenty-first century, period I (2010–2039); period II (2040–2069); and period III (2070–2099). They used the results of 11 GCMs and 2 global emissions scenarios (A2 and B1), archived from the 2007 IPCC AR4 [88]. The archived results were bias corrected and spatially and temporally downscaled, by disaggregating the values of temperature and precipitation at the GCM spatial scale in space (to the 1/2° latitude–longitude resolution) and in time (from monthly to daily), and then were used as input data of a macroscale hydrological model. The bias corrected air temperature changes, precipitation changes, and simulated main Nile stream-flow changes for some scenarios are represented in Figs. 5 and 6. These data are used in this work to modify the input files of the proposed CE-QUAL-W2 hydrodynamic and water quality model of Lake Nubia.

4.2.3 Climate Change Impacts on the Hydrodynamic Characteristics

The GCC effects on the hydrodynamic characteristics of Lake Nubia are presented in relation to the calibrated model results of the 2006 base case, which covers only 2 weeks in January 2006 (7–19 January) due to the limited availability of the

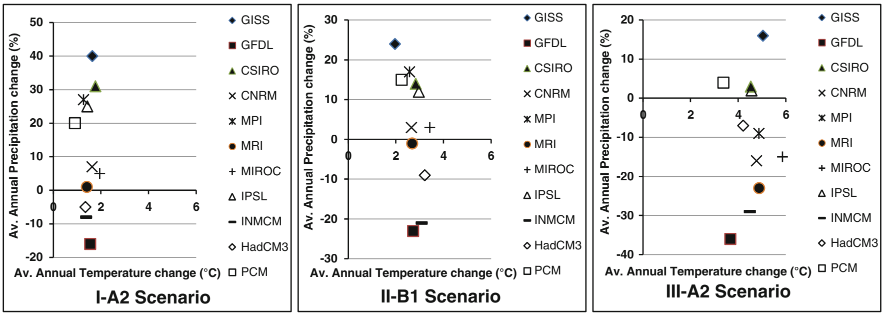

Fig. 5 Annual average change for the study area in temperature (°C) and precipitation (%) relative to 1950–1999 historical average for each GCM and some selected scenarios

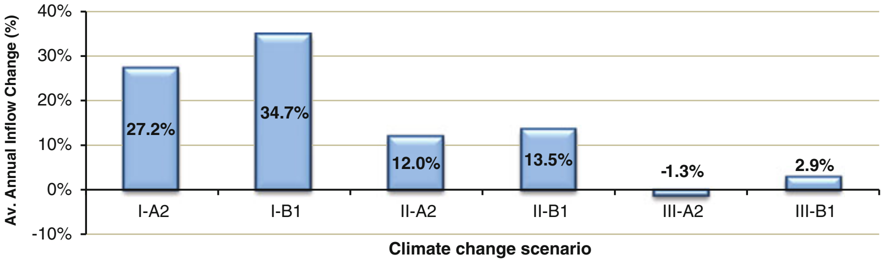

Fig. 6 Annual multi-model average change (%) for the study area in the inflow, relative to 2006 base case average for all scenarios

historical data. Hence, the future climate change scenarios cover the predicted air temperature and inflow changes for the same period of the calibration process (7–19 January). Three hydrodynamic characteristics of the reservoir are investigated with respect to the climate change: water surface levels, evaporation water losses, and thermal structure.

The predicted air temperature changes of the investigated area for different scenarios in the twenty-first century and the predicted reservoir inflow changes for the same scenarios were used to modify the input files of the calibrated base case of 2006. The future initial conditions of water temperature have been estimated by using the historical measured data base of Lake Nubia for different years. The presented results in this section were aggregately published by the author [89].

Sensitivity Analysis

A sensitivity analysis was performed using each of the predicted air temperature and inflow separately to modify the input files of the model to check its effect on water levels, evaporation water losses, and reservoir water temperature.

4.2.4 Climate Change Impacts on the Water Quality Characteristics

The climate change effects on the water quality characteristics of Lake Nubia are investigated relative to the calibrated model results of the 2006 base case. Eight water quality parameters of the reservoir were studied with respect to climate change: dissolved oxygen (DO), chlorophyll-*a* (Chl-*a*), ortho-phosphate (PO_4), nitrate–nitrite (NO_3–NO_2), ammonium (NH_4), total dissolved solids (TDS), total suspended solids (TSS), and pH.

The input files of the calibrated base case of 2006 have been modified by using the predicted air temperature and reservoir inflow for different scenarios. The future initial conditions of water temperature have been estimated by using the historical measured data base of Lake Nubia for different years. Dissolved oxygen (DO), the most important water quality parameter, was chosen to be researched due to the change of water temperature. A theoretical process algorithm has been simplified and further developed to modify the initial conditions input file of DO due to GCC effects.

DO Initial Conditions Estimation

Thomann and Mueller [90] have reported the DO sources and sinks in the water body as follows:

The DO sources are:

(1) Reaeration from the atmosphere.
(2) Photosynthetic oxygen production.
(3) DO in incoming tributaries or effluents.

While the internal sinks are:

(4) Use of oxygen for respiration by aquatic plants.
(5) Oxidation of carbonaceous waste materials.
(6) Oxidation of nitrogenous waste materials.
(7) Oxygen demand of sediments of water body.

The general mass balance equation for DO in a segment volume V can be written as:

$$V\frac{\mathrm{dDO}}{\mathrm{d}t} = \text{reaeration} + (\text{photosynthesis} - \text{respiration}) \\ -\text{oxidation of CBOD, NBOD (from inputs)} - \text{sediment oxygen demand} \\ +\text{oxygen inputs} \pm \text{oxygen transport (into and out of segment)}. \tag{1}$$

The difference of DO concentration $(\Delta \mathrm{DO}_T)$ due to the change of the water body water temperature from (T_{w1}) to (T_{w2}) can be calculated as follows:

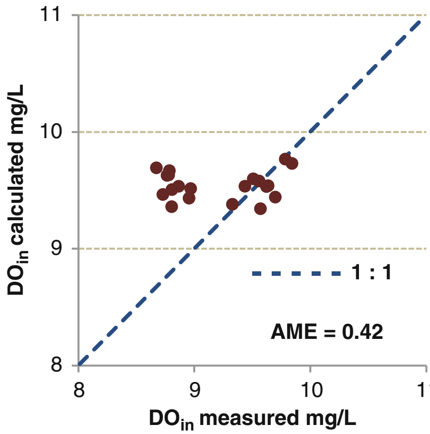

Fig. 7 Calibration of initial DO calculation algorithm for Lake Nubia using a measured data set of the year 2007

$$\begin{aligned}\Delta \mathrm{DO}_T = {} & [\text{reaeration} + (\text{photosynthesis} - \text{respiration})]_{T_{\mathrm{w1}}} \\ & -[\text{reaeration} + (\text{photosynthesis} - \text{respiration})]_{T_{\mathrm{w2}}}\end{aligned}. \tag{2}$$

This simplified (2) assumes that the other excluded sources and sinks of DO can be ignored; they are slightly influenced by the water temperature changes from (T_{w1}) to (T_{w2}).

Then by using the previous simplified theoretical process algorithm, ($\mathrm{DO}_{\mathrm{nc}}$) initial conditions at a station No. n (St. n) due to change of water temperature of base case (T_{nb}) to future climate case (T_{nc}) can be calculated as follows:

$$\mathrm{DO}_{\mathrm{nc}} = \mathrm{DO}_{\mathrm{nb}} + \Delta \mathrm{DO}_{(T_{\mathrm{nb}} - T_{\mathrm{nc}})}, \tag{3}$$

where $\mathrm{DO}_{\mathrm{nc}}$, future DO concentration initial condition at St. n; $\mathrm{DO}_{\mathrm{nb}}$, base case DO concentration initial condition at St. n; $\Delta \mathrm{DO}_{(T_{\mathrm{nb}} - T_{\mathrm{nc}})}$, DO concentration difference at St. n due to the change of water temperature at St. n from the base case (T_{nb}) to the future case (T_{nc}).

Equation (3) reduces the error of calculating the theoretical DO as much as possible.

DO Algorithm Calibration

To check the validity of the developed simplified theoretical process algorithm, a calibration process was conducted using the measured data set of Lake Nubia of the year 2007 (Fig. 7). The AME is 0.42 mg/L, which represents a reasonable error for initial condition estimation.

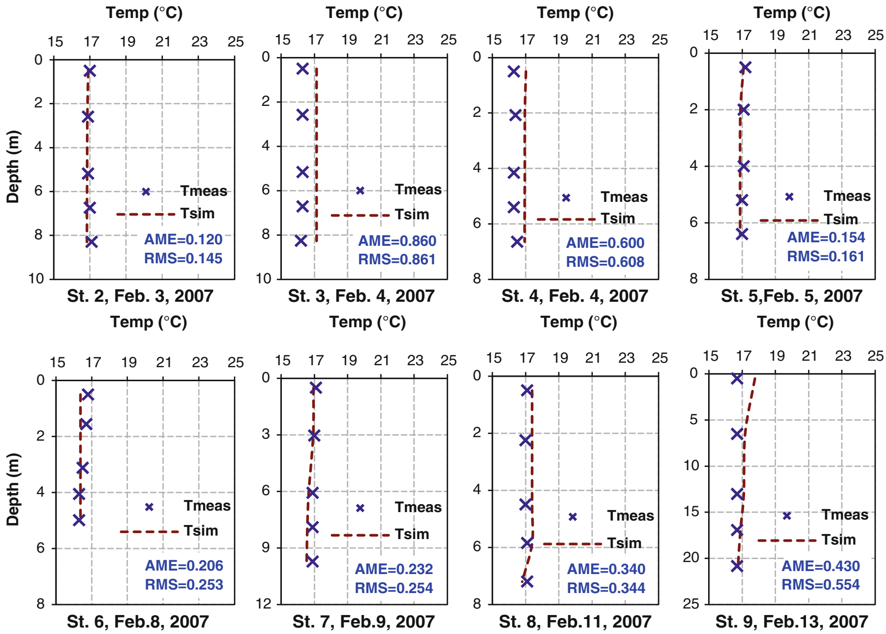

Fig. 8 Model verification: vertical profiles of water temperature (°C) in Lake Nubia at different stations and dates, February 2007

4.3 *Results and Discussion*

4.3.1 Lake Nubia Hydrodynamic and Water Quality Model

The calibrated and verified hydrodynamic model simulation shows a good agreement with the observed water surface levels and the measured water temperature profiles at various locations and dates. The vertical profiles of simulated and measured temperature at different stations for verification processes are shown in Fig. 8. The simulation results match closely the measured vertical temperature profiles. The average AME of the calibration period for the eight stations (St. 2–9) is 0.255°C, while the corresponding average RMS is 0.273°C. For the verification period, the average AME is 0.368°C and the corresponding average RMS is 0.397°C. These vertical profiles are identical to the typical thermal distribution for warm monomictic lakes in winter [91].

The water quality model reproduces spatial and temporal concentration distributions of key water quality constituents such as dissolved oxygen, chlorophyll-*a*, ortho-phosphate, nitrate–nitrite, ammonium, TDSs, total suspended solids, and pH. The model results closely mimic the measured vertical profiles of the water quality constituents. The water quality model results and field measurements of the calibration process for the second station (St. 2), as an example, are presented in vertical profiles, as shown in Fig. 9.

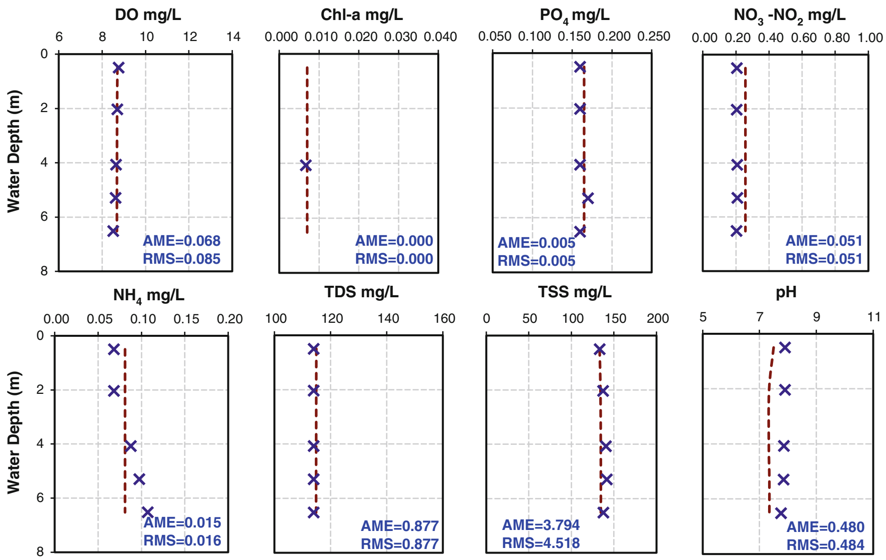

Fig. 9 Model calibration: vertical profiles of measured (*multiplication sign*) and simulated (*broken line*) key water quality parameters in Lake Nubia at St. 2 on 8 January 2006

4.3.2 Climate Change Impacts on the Hydrodynamic Characteristics

Figure 10 shows the reservoir water levels change in %, relative to the stations water depths of the base case, for some selected scenarios. Five of six scenarios produce higher reservoir water levels than the base case, while the (III-A2) scenario, period III (2070–2099) with A2 global emission scenario, produces slightly lower reservoir water levels. The increase or decrease of the reservoir water levels varies from station to station depending on the station morphological characteristics. The figure shows that maximum water level change will be 3% for scenario I-B1, which has the maximum predicted annual inflow to the reservoir (+34.7%), at St. 4 which has the smallest cross section area, according to the reservoir bathymetry. As shown in Fig. 6, these results are directly proportional to the hydrological model inflow predictions.

The reservoir evaporation water losses change (%) is shown in Fig. 11 for all scenarios. The figure shows that the maximum evaporation water losses change for the reservoir will be 7.7% for scenario III-A2 which has the maximum predicted air temperature change (3.9°C). The evaporation water losses change is directly proportional to the air temperature change.

Reservoir water temperature profiles for some selected scenarios and stations are presented in Fig. 12. ΔT is the average change (%) between the simulated base case and the simulated climate change scenario case. The reservoir water temperature is directly proportional to the air temperature and the reservoir surface area and inversely proportional to the predicted inflow [92]. The reservoir water temperature

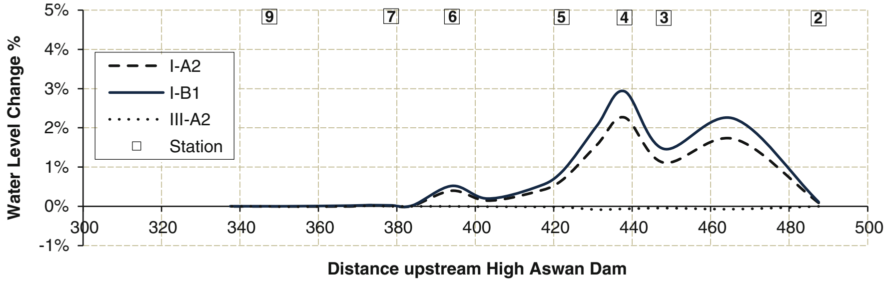

Fig. 10 Lake Nubia water levels change (%) due to climate change for some selected scenarios

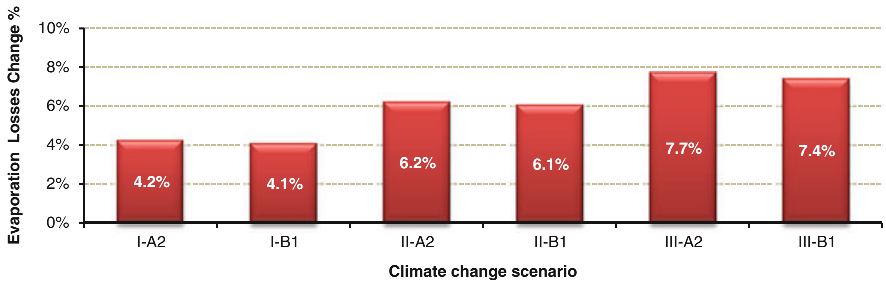

Fig. 11 Lake Nubia evaporation water losses change (%) due to climate change for all scenarios

change varies depending on the reservoir morphological and hydrological characteristics, for instance St. 5 has the smallest surface area and a higher water velocity (relative to the other stations) which enable it to have the minimum average difference (−7.42%) for scenario I-B1 which has the maximum predicted annual inflow (+34.7%). While the maximum average difference (5.91%) will be found at St. 7, which has a higher surface area, for III-A2 scenario which has the minimum predicted annual inflow to the lake (−1.3%).

Sensitivity Analysis

Figure 13 presents the longitudinal water surface levels average difference profiles for some selected climate change scenarios. For all scenarios considering only the temperature effects, such as T I-A2 and T I-B1, there will be no change in the reservoir water levels. As can be seen in the current figure, the water level changes are directly proportional to the predicted inflow.

Lake Nubia evaporation water losses change (%) due to GCC, air temperature effect only, for all scenarios can be seen in Fig. 14. Comparison with Fig. 11, which presents the evaporation water losses change due to the effect of both air temperature and inflow, shows higher values. This difference is caused by the direct

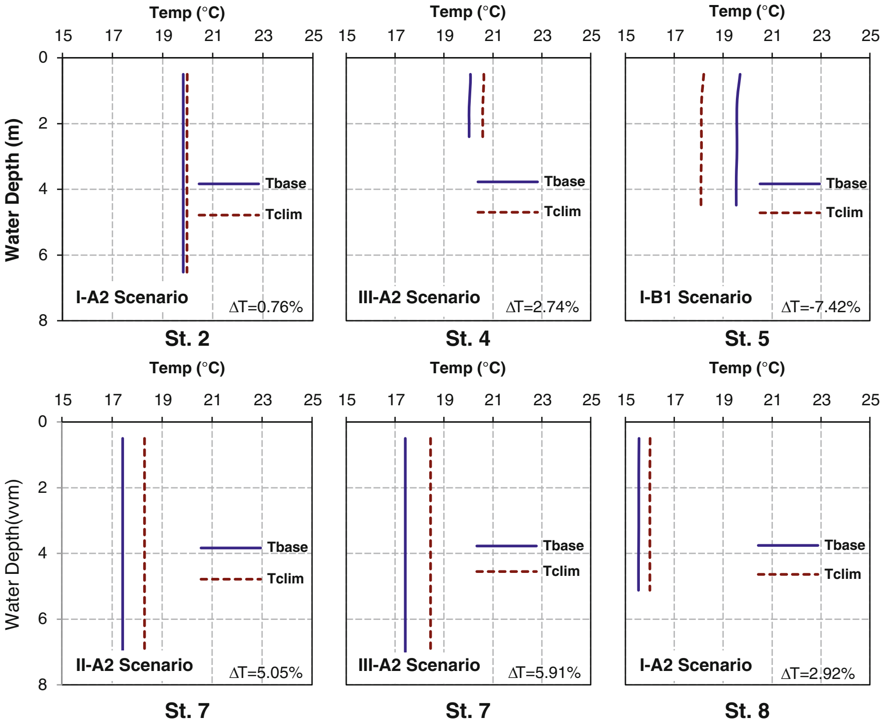

Fig. 12 Lake Nubia water temperature (°C) profiles due to global climate change (*broken line*) for some selected scenarios and stations, compared with the simulated base case (*continuous line*)

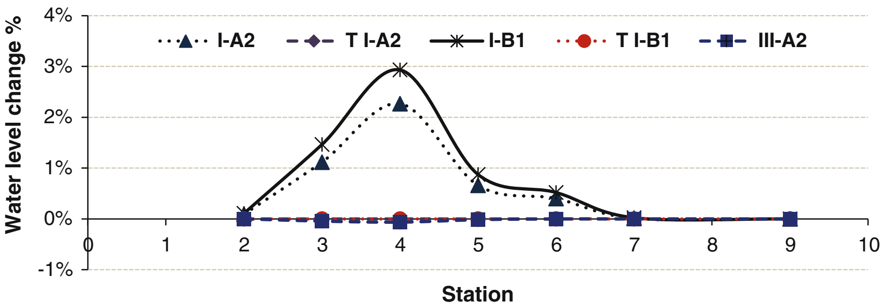

Fig. 13 Lake Nubia water levels change (%) due to global climate change for some selected scenarios

relationship between evaporation water losses and the reservoir inflow which affect the morphological characteristics of the reservoir.

Figure 15 presents longitudinal profiles of the average water temperature change (%) due to GCC. Here, the air temperature effect was only considered. The average

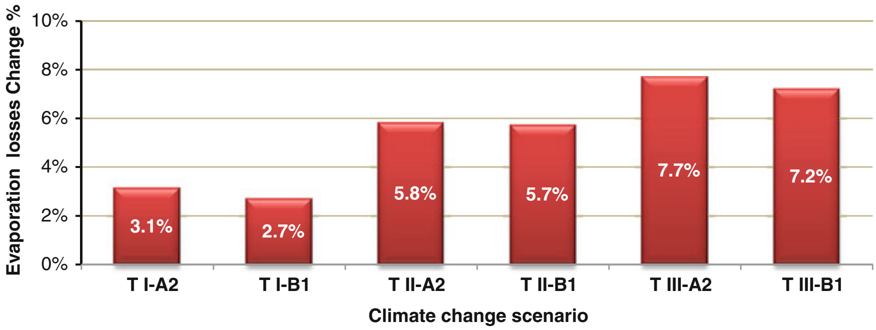

Fig. 14 Lake Nubia evaporation water losses change (%) due to global climate change, air temperature effect only, for all scenarios

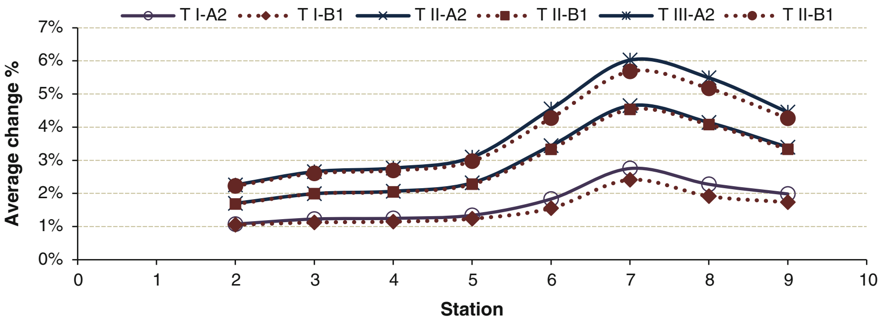

Fig. 15 Lake Nubia average water temperature change (%) longitudinal profiles due to global climate change, air temperature effect only, for all scenarios

water temperature change longitudinal profiles due to the effect of both air temperature and reservoir inflow are shown in Fig. 16.

It can be noticed that, as discussed before, the reservoir water temperature is directly proportional to the air temperature and inversely proportional to the predicted inflow. The reservoir water temperature change varies depending on the morphological characteristics which are influenced by the reservoir inflow.

4.3.3 Climate Change Impacts on the Water Quality Characteristics

Figures 17, 18, and 19 show profiles of the Lake Nubia water quality characteristics due to GCC for some selected scenarios and stations. ΔC is the average change (%) between the simulated base case of the year 2006 and the simulated scenario case.

DO change is inversely proportional to water temperature change and inflow change. As can be seen in figures, the average changes of DO will decrease by 0.23%, 2.75%, and 2.17% when water temperature average change increases by 1.68%, 1.78%, and 5.49% at St. 4, St. 7, and St. 8 for scenarios II-B1, I-B1, and

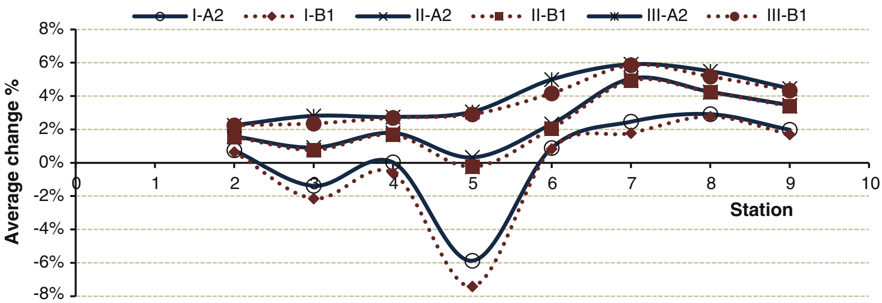

Fig. 16 Lake Nubia average water temperature change (%) longitudinal profiles due to global climate change, air temperature, and reservoir inflow, for all scenarios

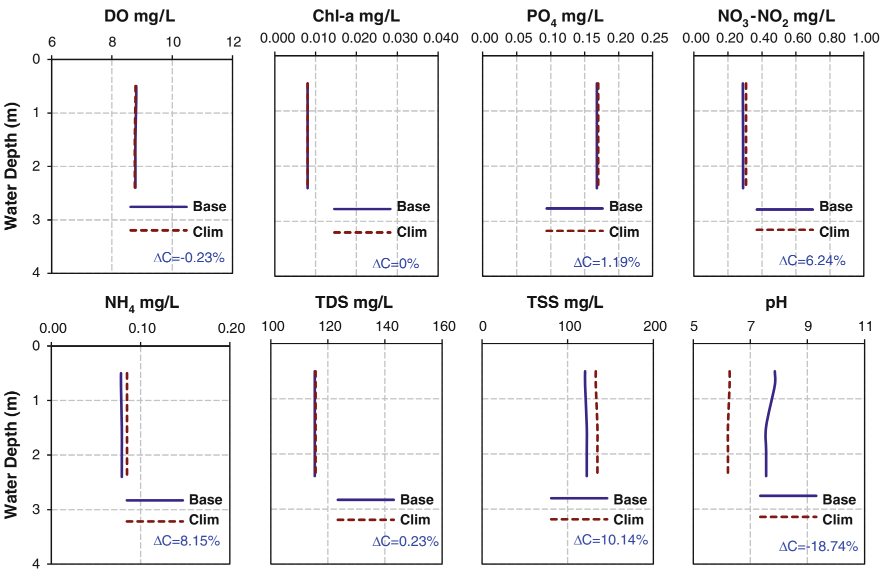

Fig. 17 Lake Nubia water quality characteristics profiles due to global climate change (*broken line*) for II-B1 scenario at St. 4, compared with the simulated base case (*continuous line*)

III-A2, respectively. While the inflow changes will be +13.5, +34.7, and −1.3 for scenarios II-B1, I-B1, and III-A2, respectively.

The biological activity (i.e., photosynthesis and respiration) is affected by water temperature change and inflow change. As water temperature rises, the metabolic rates of the most water organisms increase. When inflow change increases, suspended solids increase and affect the euphotic zone depth and then algal biomass. Moreover, inflow change affects the phytoplankton stability. Chlorophyll-*a* is an indirect measure of algal biomass, the negative changes of chlorophyll-*a* in Figs. 17, 18, and 19 are due to the inflow change, such as at St. 7 for scenario I-B1 (inflow change will be 34.7%), or due to the decrease of DO, such as

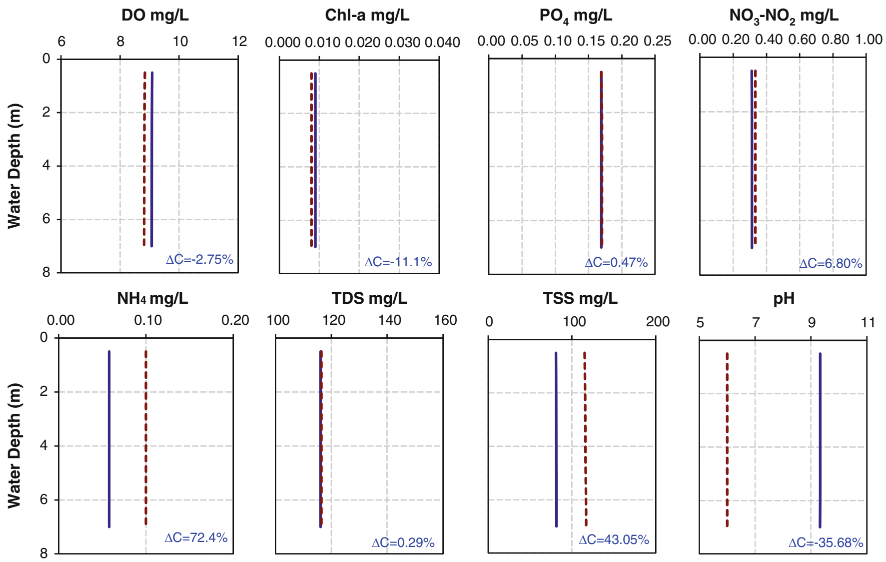

Fig. 18 Lake Nubia water quality characteristics profiles due to global climate change (*broken line*) for I-B1 scenario at St. 7, compared with the simulated base case (*continuous line*)

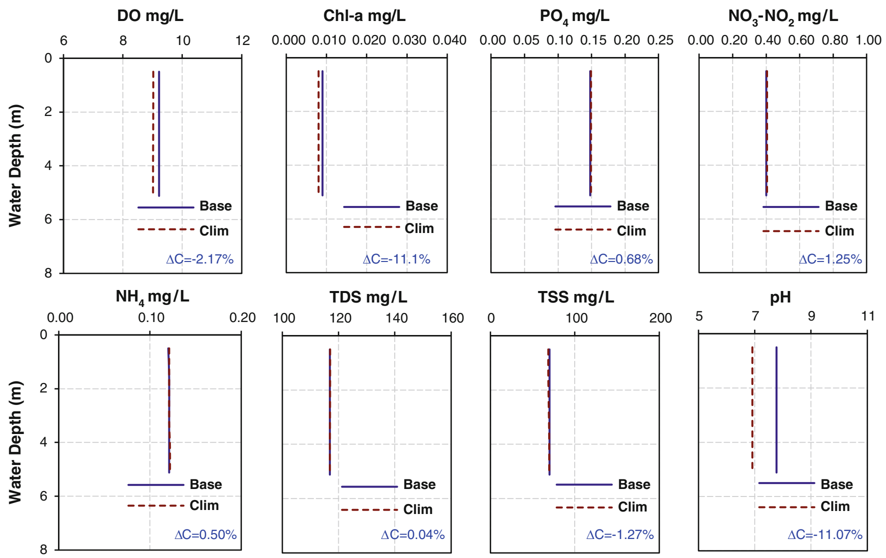

Fig. 19 Lake Nubia water quality characteristics profiles due to global climate change (*broken line*) for III-A2 scenario at St. 8, compared with the simulated base case (*continuous line*)

at St. 8 for scenario III-A2 where DO change will decrease by 2.17% which will affect the respiration and decomposition processes.

Inflow changes affect nutrients concentrations in the water body. When inflow increases, surface erosion from the catchment (soil leaching) increases and then nitrate–nitrite, ammonium, and phosphate concentrations will increase. Such as at St. 4 and St. 7 where inflow change increases by 13.5% and 34.7%, respectively. The ammonium and nitrate–nitrite concentration changes are controlled by the DO change which affects the nitrification process; when DO change decreases, nitrification process decreases and then ammonium concentration increases while nitrate–nitrite decreases. Increase in the nutrients concentrations can be noticed at St. 8 due to the decrease of algae biomass.

Suspended solids change is directly proportional mainly to the inflow change, as can be seen in Figs. 17, 18, and 19. When inflow increases, inflow velocity increases and settlement velocity of suspended solids decreases, hence suspended solids concentration increases. pH is affected by water temperature, dissolved solids, alkalinity, and total inorganic carbon. At St. 4 and St. 7 for scenarios II-B1 and I-B1, respectively, inflow changes increase which increase total solids concentrations and different ions (by soil leaching), hence resulted in lower pH. For scenario III-A2 at St. 8, pH will decrease due to increase of total inorganic carbon average change by 30.44% as a result of water temperature increase which increases the metabolic activity.

5 Conclusions and Recommendations for Future Work

One of the main goals of this research work is to quantify the potential impact of the GCC on hydrodynamic and water quality characteristics of Lake Nubia. In doing so, we recognize the limitations of this modeling approach including the uncertainty in GCMs output, the hydrological model, and the hydrodynamic and water quality model. Thus, the results presented here are an indication of the effects of climate change on hydrodynamic and water quality characteristics of Lake Nubia, and are not intended to be exact predictions.

The impacts of climate change on hydrodynamic and water quality characteristics of Lake Nubia were investigated using a proposed hydrodynamic and water quality model, which simulates three periods: I [2010–2039], II [2040–2069], and III [2070–2099] – with two emission scenarios, A2 and B1, for each period, including the average of 11 GCMs outputs. A theoretical process algorithm has been simplified and further developed to modify the initial conditions input file of dissolved oxygen due to GCC effects. A sensitivity analysis has been done by using each of predicted air temperature and inflow separately to check its effect on the hydrodynamic characteristics. The GCC effects are presented relative to the calibrated model results of the year 2006 base case.

It is emphasized that the calibration and the scenarios cover only a short period of 2 weeks of simulation. This is due to the limited availability of historic data.

Consequently the results and quantified effects do not reflect the variability of hydrodynamics and water quality extending over 1 year or even longer periods. Such an extension is recommended as essential future work.

The effects of GCC on three hydrodynamic characteristics of Lake Nubia were investigated. The studied hydrodynamic characteristics are water levels, evaporation water losses, and reservoir thermal structure. The results of the climate change show that there are significant impacts on the examined characteristics. Thus, it can be concluded that:

(1) Water level changes are directly proportional to the hydrological model inflow predictions. The maximum water level change will be 3% for scenario I-B1 at St. 4.
(2) The evaporation water losses change is directly proportional to the air temperature change. The evaporation water losses are higher than the base case for all scenarios, the maximum evaporation water losses change for the reservoir will be 7.7% for scenario III-A2.
(3) The reservoir water temperature changes are directly proportional to the air temperature changes and the reservoir surface area and inversely proportional to the predicted inflow changes. The maximum water temperature change will be 5.9% for scenario III-A2 at St. 7, while the minimum change will be −7.4% for scenario I-B1 at St. 5.

The GCC effects on the water quality characteristics of Lake Nubia are investigated relative to the calibrated model results of the 2006 base case. Eight water quality parameters of the reservoir were studied with respect to climate change: DO, Chl-*a*, PO_4, NO_3–NO_2, NH_4, TDS, TSS, and pH. From the results, it can be concluded that climate change has clear impacts on the investigated parameters as follows:

(1) The change of DO is inversely proportional to water temperature and inflow changes. The maximum DO average decrease will be 3.9% at St. 8 for I-B1, while the maximum DO average increase will be 2.9% for I-B1 scenario at St. 9.
(2) Biological activity (i.e., photosynthesis and respiration) is affected by water temperature change and inflow change. Chl-*a* will decrease by 11% at St. 7 and St. 8 for scenarios I-B1 and III-A2, respectively.
(3) Inflow changes affect the nutrients concentrations in the water body. For the maximum predicted inflow scenario I-B1 at St. 7, PO_4 will have an increase of 0.5% while NH_4 and NO_3–NO_2 will increase by 72.4% and 6.8%, respectively.
(4) Suspended solids change is directly proportional mainly to the inflow change. For the maximum predicted inflow scenario I-B1 at St. 7, TSS and TDS will increase by 43% and 0.3%, respectively.
(5) pH is affected by water temperature, dissolved solids, alkalinity, and total inorganic carbon. When inflow changes increase, total solids concentrations with different ions (by soil leaching) increase, hence pH decreases such as for I-B1 scenario at St. 7, pH will decrease by 35.7%.

5.1 Recommendations for Future Work

(1) Long-term records of hydrodynamic and water quality characteristics of the AHDR are urgently required to investigate in more detail the climate change impacts based on a much longer period of simulation than it could be realized in this research work due to the very limited historical data base being presently available.
(2) A RCM for the Nile Basin should be developed to estimate changes of different meteorological parameters. The results of this RCM may be used to simulate the runoff pattern by using a suitable hydrological model.
(3) Daily records of hydrodynamic and water quality characteristics of the AHD Reservoir for 1 year, at least, should be examined to investigate climate change impacts of the reservoir thermal structure and the water column stability.

References

1. Van der Geest K (2002) We are managing!? Vulnerability and responses to climate variability and change among rural households in Northwest Ghana. MSc, University of Amsterdam, Amsterdam
2. CECC (2008) Ecological impacts of climate change. National Academies Press, Washington
3. IPCC (2007) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
4. IPCC (2007) Climate change 2007: mitigation of climate change. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York
5. Houghton JT (2004) Global warming: the complete briefing, 3rd edn. Cambridge University, Cambridge
6. SRES website Sres. IPCC special report on emissions scenarios. This report was first released for COP 6 in The Hague, November 2000, and was prepared and published to web by GRID-Arendal in 2001. http://www.grida.no/climate/ipcc/emission
7. van Storch H (2008) Climate change scenarios – purpose and construction. In: van Storch H, Tol RSJ, Flöser G (eds) Environmental crises. Springer, Berlin, p 142
8. USEPA (2009) USEPA. Frequently asked questions about global warming and climate change: back to basics. http://www.epa.gov/climatechange/downloads/Climate_Basics.pdf
9. Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miller KA, Oki T, Sen Z, Shiklomanov IA (2007) Freshwater resources and their management. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 976
10. Rosenzweig C, Casassa G, Karoly DJ, Imeson A, Liu C, Menzel A, Rawlins S, Root TL, Seguin B, Tryjanowski P (2007) Assessment of observed changes and responses in natural and managed systems. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 976

11. Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water: technical paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva
12. EEA (2007) Climate change and water adaptation issues. EEA Technical report No. 2/2007. EEA, Copenhagen
13. Gleick P (1987) Global climatic changes and regional hydrology: impacts and responses. Paper presented at the influence of climate change and climatic variability on the hydrologie regime and water resources (Proceedings of the Vancouver Symposium, August 1987). IAHS publication no. 168, pp 389–402
14. Gleick PH (1998) Water planning and management under climate change. Water Resources Update 112:25–32
15. Grimm NB, Chacón A, Dahm CN, Hostetler SW, Lind OT, Starkweather PL, Wurtsbaugh WW (1997) Sensitivity of aquatic ecosystems to climatic and anthropogenic changes: the basin and range, American southwest and Mexico. Hydrol Process 11:1023–1041
16. Mulholland PJ, Best GR, Coutant CC, Hornberger GM, Meyer JL, Robinson PJ, Stenberg JR, Turner RE, Vera-Herrera F, Wetzel RG (1997) Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrol Process 11:949–970
17. Murdoch PS, Baron JS, Miller TL (2000) Potential effects of climate change on surface-water quality in North America. J Am Water Resour Assoc 36:347–366
18. Schindler DW (1997) Widespread effects of climatic warming on freshwater ecosystems in North America. Hydrol Process 11:1043–1067
19. Whitehead PG, Wilby RL, Battarbee RW, Kernan M, Wade aJ (2009) A review of the potential impacts of climate change on surface water quality. Hydrol Sci J 54:101–123
20. Delpla I, Jung a-V, Baures E, Clement M, Thomas O (2009) Impacts of climate change on surface water quality in relation to drinking water production. Environ Int 35:1225–1233
21. Gleick P (1989) Climate change, hydrology, and water resources. Rev Geophys 27:329–344
22. Leavesley GH (1994) Modeling the effects of climate change on water resources-a review. Clim Chang 28:159–177
23. Varis O, Kajander T, Lemmelä R (2004) Climate and water: from climate models to water resources management and vice versa. Clim Chang 66:321–344
24. Block PJ, Souza Filho FA, Sun L, Kwon H-H (2009) A streamflow forecasting framework using multiple climate and hydrological models. J Am Water Resour Assoc 45:828–843
25. Christensen NS, Wood AW, Voisin N, Lettenmaier DP, Palmer RN (2004) The effects of climate change on the hydrology and water resources of the Colorado river basin. Clim Chang 62:337–363
26. Middelkoop H, Daamen K, Gellens D, Grabs W, Kwadijk JCJ, Lang H, Parmet BWAH, Schädler B, Wilke JS II, Wilke K (2001) Impact of climate change on hydrological regimes and water resources management in the Rhine basin. Clim Chang 49:105–128
27. Hondzo M, Stefan H (1993) Regional water temperature characteristics of lakes subjected to climate change. Clim Chang 24:187–211
28. Coats R, Perez-Losada J, Schladow G, Richards R, Goldman C (2006) The warming of lake Tahoe. Clim Chang 76:121–148
29. Fukushima T, Ozaki N, Kaminishi H, Harasawa H, Matsushige K (2000) Forecasting the changes in lake water quality in response to climate changes, using past relationships between meteorological conditions and water quality. Hydrol Process 14:593–604
30. George G, Hurley M, Hewitt D (2007) The impact of climate change on the physical characteristics of the larger lakes in the English Lake District. Freshw Biol 52:1647–1666
31. Koinig KA, Schmidt R, Sommaruga-Wögrath S (1998) Climate change as the primary cause for pH shifts in a high Alpine lake. Zoology 104:167–180
32. Livingstone DM (2003) Impact of secular climate change on the thermal structure of a large temperate Central European lake. Clim Chang 57:205–225
33. O'Reilly CM, Alin SR, Plisnier P-D, Cohen AS, McKee BA (2003) Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. Nature 424:766–768

34. Ozaki N, Fukushima T, Harasawa H, Kojiri T, Kawashima K, Ono M (2003) Statistical analyses on the effects of air temperature fluctuations on river water qualities. Hydrol Process 17:2837–2853
35. Sahoo GB, Schladow SG (2008) Impacts of climate change on lakes and reservoirs dynamics and restoration policies. Sustain Sci 3:189–199
36. Troin M, Vallet-Coulomb C, Sylvestre F, Piovano E (2008) Response of Lake Mar Chiquita in Argentina to climate change: data analysis and application of a lake model. In: 13th IWRA world water congress, Montpellier, pp 1–11
37. Anderson J, Chung F, Anderson M, Brekke L, Easton D, Ejeta M, Peterson R, Snyder R (2008) Progress on incorporating climate change into management of California's water resources. Clim Chang 87:91–108
38. Fang X, Shrestha R, Groeger AW, Lin C-J, Jaol M (2007) Simulation of impacts of stream flow and climate conditions on Amistad reservoir. J Contemp Water Res Educ 137:14–20
39. Fang X, Stefan HG (1999) Projections of climate change effects on water temperature characteristics of small lakes in the contiguous US. Clim Chang 42:377–412
40. Gooseff MN, Strzepek K, Chapra SC (2005) Modeling the potential effects of climate change on water temperature downstream of a shallow reservoir, lower Madison River, MT. Clim Chang 68:331–353
41. Hassan H, Aramaki T, Hanaki K, Matsuo T, Wilby R (1998) Lake stratification and temperature profiles simulated using downscaled GCM output. Water Sci Technol 38:217–226
42. Qin B, Huang Q (1998) Evaluation of the climatic change impacts on the inland lake–a case study of Lake Qinghai, China. Clim Chang 39:695–714
43. Sinokrot B, Stefan H, McCormick J, Eaton J (1995) Modeling of climate change effects on stream temperatures and fish habitats below dams and near groundwater inputs. Clim Chang 30:181–200
44. Stefan H, Fang X, Hondzo M (1998) Simulated climate change effects on year-round water temperatures in temperate zone lakes. Clim Chang 40:547–576
45. Chang L, Railsback S, Brown R (1992) Use of a reservoir water quality model to simulate global climate change effects on fish habitat. Clim Chang 20:277–296
46. Fang X, Stefan HG, Eaton JG, McCormick JH, Alam SR (2004) Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios part 1. Cool-water fish in the contiguous US. Ecol Model 172:13–37
47. Fang X, Stefan HG, Eaton JG, McCormick JH, Alam SR (2004) Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios part 3. Warm-water fish in the contiguous US. Ecol Model 172:55–68
48. Fang X, Stefan HG, Eaton JG, McCormick JH, Alam SR (2004) Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios part 2. Cold-water fish in the contiguous US. Ecol Model 172:39–54
49. Hassan H, Hanaki K, Matsuo T (1998) A modeling approach to simulate impact of climate change in lake water quality: phytoplankton growth rate assessment. Water Sci Technol 37:177–185
50. Hosomi M, Saigusa T, Yabunaka K, Okubo T, Murakami A (1996) Development of a water temperature-ecological model to stimulate global warming effects on lake ecosystem. Water Sci Technol 34:237–244
51. Komatsu E, Fukushima T, Harasawa H (2007) A modeling approach to forecast the effect of long-term climate change on lake water quality. Ecol Model 209:351–366
52. Malmaeus J, Blenckner T, Markensten H, Persson I (2006) Lake phosphorus dynamics and climate warming: a mechanistic model approach. Ecol Model 190:1–14
53. Svendsen M, Künkel N (2008) Water and adaptation to climate change: consequences for developing countries. GTZ, Germany
54. Attia BB (2008) Assessment of vulnerability and adaptation of water resources to climate change in Egypt. In: 13th IWRA world water congress, Montpellier, France

55. EEAA (1999) The Arab republic of Egypt: initial national communication on climate change under the United Nations framework convention on climate change. Egyptian Environmental Affairs Agency (EEAA), Cairo
56. EEAA (2010) Egypt second national communication under the United Nations framework convention on climate change. Egyptian Environmental Affairs Agency (EEAA), Cairo
57. Riebsame WE, Strzepek KM, Wescoat JL Jr, Perritt P, Gaile GL, Jacobs J, Leichenko R, Magadza C, Phien H, Urbiztondo BJ, Restrepo P, Rose WR, Saleh M, Ti LH, Tucci C, Yates D (1995) Complex river basins. In: Strzepek KM, Smith JB (eds) As climate changes: international impacts and implications. USEPA, Cambridge; New York, p 213
58. Abu-Zeid MA, Biswas AK (1991) Some major implications of climatic fluctuations on water management. Int J Water Resour Dev 7:74–81
59. Conway D, Hulme M (1993) Recent fluctuations in precipitation and runoff over the Nile sub-basins and their impact on main Nile discharge. Clim Chang 25:127–151
60. Jeuland M, Whittington D (2008) Climate change implications for water resources planning in transboundary water systems. In: Fourth international symposium on transboundary waters management, Thessaloniki
61. Strzepek K, Yates D (2000) Responses and thresholds of the Egyptian economy to climate change impacts on the water resources of the Nile River. Clim Chang 46:339–356
62. Strzepek K, Yates D, Yohe G, Tol R, Mader N (2001) Constructing "not implausible" climate and economic scenarios for Egypt. Integr Assess 2:139–157
63. Yates D, Strzepek K (1998) An assessment of integrated climate change impacts on the agricultural economy of Egypt. Clim Chang 38:261–287
64. Yates DN, Strzepek KM (1996) Modeling economy-wide climate change impacts on Egypt: a case for an integrated approach. Environ Model Assess 1:119–135
65. Abou Hadid AF (2006) Assessment of impacts, adaptation, and vulnerability to climate change in North Africa: food production and water resources. Evaluation. The International START Secretariat, Washington
66. Abou Hadid AF, Eid HM (2006) Egypt. In: van Drunen MA, Lasage R, Dorland C (eds) Climate change in developing countries: results from the Netherlands climate change studies assistance programme. CABI Publication, Wallingford, p 190
67. El-Shaer H, Rosenzweig C, Iglesias A, Eid M, Hillel D (1997) Impact of climate change on possible scenarios for Egyptian agriculture in the future. Mitig Adapt Strat Glob Chang 1:233–250
68. Mougou R, Abou-Hadid A, Iglesias A, Medany M, Nafti A, Chetali R, Mansour M, Eid H (2008) Adapting dryland and irrigated cereal farming to climate change in Tunisia and Egypt. In: Leary N, Adejuwon J, Barros V, Burton I, Kulkarni J, Lasco R (eds) Climate change and adaptation. Earthscan, London, p 381
69. Gleick PH (1991) The vulnerability of runoff in the Nile Basin to climatic changes. Environ Prof 13:66–73
70. Conway D, Hulme M (1996) The impacts of climate variability and future climate change in the Nile Basin on water resources in Egypt. Int J Water Resour Dev 12:277–296
71. Strzepek K, Yates D, El Quosy D (1996) Vulnerability assessment of water resources in Egypt to climatic change in the Nile Basin. Clim Res 6:89–95
72. Agrawala S, Moehner A, Raey ME, Conway D, Aalst MV, Hagenstad M, Smith J (2004) Development and climate change in Egypt: focus on coastal resources and the Nile. Organisation for Economic Co-operation and Development, Paris
73. Conway D (2005) From headwater tributaries to international river: observing and adapting to climate variability and change in the Nile Basin. Glob Environ Change A 15:99–114
74. Mohamed YA, van den Hurk BJJM, Savenije HHG, Bastiaanssen WGM (2005) Hydroclimatology of the Nile: results from a regional climate model. Hydrol Earth Syst Sci 9:263–278
75. Soliman ESA, Sayed MAA, Nour El-Din MM, Samy G (2008) Integration of NFS with regional climate model to simulate the Nile Basin hydro-climatology. Nile Basin Water Eng Sci Mag 1:75–85

76. Sayed MAA (2008) Eastern Nile planning model, integration with IDEN projects to deal with climate change uncertainty and flooding risk. Nile Basin Water Eng Sci Mag 1:86–93
77. Kim U, Kaluarachchi JJ (2009) Climate change impacts on water resources in the upper Blue Nile river basin, Ethiopia. J Am Water Resour Assoc 45:1361–1378
78. Elshamy ME, Seierstad IA, Sorteberg A (2009) Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. Hydrol Earth Syst Sci Discuss 13:551–565
79. Elshamy ME, Sayed MA-A, Badawy B (2009) Impacts of climate change on the Nile flows at Dongola using statistical downscaled GCM scenarios. Nile Basin Water Eng Sci Mag 2:1–14
80. Radwan M (2009) Global warming impacts on water quality in the Nile Delta, Egypt. Nile Basin Water Eng Sci Mag 2:71–78
81. Beyene T, Lettenmaier DP, Kabat P (2010) Hydrologic impacts of climate change on the Nile River Basin: implications of the 2007 IPCC scenarios. Clim Chang 100:433–461
82. MWRI (2005) Water for the future, national water resources plan for Egypt – 2017, Ministry of Water Resources and Irrigation, Arab Republic of Egypt
83. Abdel Latif AF (1984) Lake Nasser – the new man-made lake in Egypt (with reference to Lake Nubia). In: Taub FB (ed) Lakes and reservoirs, vol 23, Ecosystems of the world. Elsevier, Amsterdam
84. Elshemy M, Le TTH, Meon G, Heikal M (2010) Water quality modeling for the southern part of Aswan High Dam Reservoir, Lake Nubia. Paper presented at the First European IAHR congress, Edinburgh, UK, 4–6 May 2010; 25–26 March
85. Cole TM, Wells SA (2008) Ce-qual-w2: a two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.6. Department of Civil and Environmental Engineering, Portland State University, Portland
86. Weather Underground Weather underground. http://www.wunderground.com/
87. Cole TM, Tillman DH (2001) Water quality modeling of Allatoona and West Point Reservoirs using ce-qual-w2. Environmental Laboratory, U.S. Army Engineer Research and Development Center, vol Report EL SR-01-3, Final report edition
88. PCMDI website Pcmdi. Program for climate model diagnosis and intercomparison. http://www-pcmdi.llnl.gov/
89. Elshemy M, Meon G (2010) Climate change impacts on the hydrodynamic characteristics of the southern part of Aswan High Dam reservoir, Lake Nubia. Paper presented at the sixth international symposium on environmental hydraulics, Athens, 23–25 June 2010
90. Thomann RV, Mueller JA (1987) Principles of surface water quality modeling and control. Harper and Row, New York
91. Thomas R, Meybeck M, Beim A (1996) Lakes. In: Chapman DV (ed) Water quality assessments: a guide to the use of biota, sediments and water in environmental monitoring. Spon, London
92. Chapra SC (1997) Surface water-quality modeling. McGraw-Hill series in water resources and environmental engineering. McGraw-Hill, New York

Modeling Climate Change Impacts and Adaptation Strategies for Crop Production in Egypt: An Overview

Samiha Ouda, Gamal El-Afandi, and Tahany Noreldin

Abstract Understanding the potential impacts of climate change is very important in developing adaptation strategies and actions to reduce future climate change risks. In recent years, global climate change models have been used in Egypt to develop climate change scenarios. The objective of this chapter is to highlight the importance of using global climate change models to quantify the risk of climate change on wheat and maize production in Egypt. Field experiments data from case study sites located in four geographically different Egypt Governorates and CropSyst model output are incorporated in a climate change model to assess the effect of climate change scenarios and adaptation strategies on wheat and maize production in Egypt. Results show that the yield of both crops will be reduced under future climate change scenarios. The level of yield reduction depends on geographic location, soil type, and irrigation method. The model shows higher yield loss in the Middle of Egypt as compared to the North of Egypt. Furthermore, the model predicts higher yield losses for crops grown on sandy soils and under flood irrigation. It is concluded that it is necessary to improve adaptation to present day climate variability in order to reduce vulnerability to extreme events due to future climate change.

Keywords CropSyst model, Egypt, HadCM3 model, Irrigation systems, Maize, Wheat

---

S. Ouda (✉)
Water Requirements and Field Irrigation Research Department, Soils, Water, and Environment Research Institute, Agricultural Research Center, Giza, Egypt
e-mail: samihaouda@yahoo.com

G. El-Afandi
Department of Astronomy and Meteorology, Al Azhar University, Cairo Governorate, Egypt

T. Noreldin
Crop Physiology Department, Field Crops Research Institute, Agricultural Research Center, Giza, Egypt

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 99–120, DOI 10.1007/698_2013_226,

Contents

1 Introduction

It is reported that burning of fossil fuels and rapid deforestation, over the past 200 years, has caused increased concentrations of heat-trapping "greenhouse gases" in the Earth's atmosphere and consequently a rise in the Earth's temperature, 0.7°C on average since 1900 [1, 2]. Worldwide records show increase in heat waves, fewer frosts, warming of the lower atmosphere and upper oceans, retreat of glaciers and sea-ice, rise in global sea-level and increased high intensity rainfall in many regions [3, 4]. Furthermore, many species of plants and animals have changed their location or behavior in ways that provide further evidence of climate change [5].

Sustainable development is defined as the development that meets the needs of present generation without compromising the needs of future generations [6]. Climate change is expected to modify the social, economic, and environmental dimensions of sustainable development and therefore will alter the potential development pathways. Since agriculture is an activity dependent on climate, future climate change could alter the conditions for crop production and increase its vulnerability, which will affect worldwide food security [7]. Many factors that determine a country's ability to promote sustainable development coincide with factors that influence adaptive capacity relative to climate change, climate variability, and climatic extremes [6].

Crop production is affected biophysically by changing meteorological variables, including rising temperatures, changing precipitation regimes, and increasing levels of atmospheric carbon dioxide. Changes in yield behavior in relation to shifts in climate can become critical for farm economy. An increasing probability of low returns as a consequence of more frequent occurrence of adverse conditions could prove dramatic for farmers operating at the limit of economic stress [8]. In Egypt, many studies have predicted the implications of climate change on the yield of several crops and raised a sensible anxiety about the threat of climate change to sustainable development. Furthermore, these studies have revealed that yields and water use efficiency will be decreased in comparison with current climate conditions, even when the beneficial effects of CO_2 are taken into account [9].

Adaptation refers to efforts to reduce system's vulnerabilities to climate change. According to IPCC [1], adaptation is concerned with responses to both the negative and positive effects of climate change. It refers to any adjustments whether passive, reactive, or anticipatory that can respond to anticipated or actual consequences associated with climate change. Thus, it implicitly recognizes that future climate change will occur and must be accommodated in policy.

Adaptation to climate change has received little attention compared with mitigation. This may be partly because adaptation seems more complicated than mitigation. While emission sources are relatively few and perhaps controllable, there are vast array of rather complicated adaptation strategies. Yet to ignore adaptation is both unrealistic and perilous [10]. A wide range of responses can be implemented exogenously by management or policy decisions at the regional or national level [11]. Agricultural adaptation to climate change at the farm level depends on the technological potential such as different varieties of crops and irrigation management, soil and water condition, and biological response. The capability of farmers to detect climate change and undertake any necessary actions can be reflected on achieving high *crop water productivity*. This is a quantitative term that defines the relationship between the amounts of water supplied and crop produced [12]. It is a useful indicator for quantifying the impact of irrigation scheduling decisions, with regard to efficient water management.

2 Climate Change Models and Scenarios

To predict future climate change, scientists have developed greenhouse gas (GHG) and aerosol emission prediction scenarios for the twenty-first century. Predictive models and scenarios allow analysis of "what if?" questions based on various assumptions about human behavior, economic growth, and technological change [13]. The most widely utilized tools for simulating climate change are general circulation models (GCMs), atmospheric ceneral circulation Model (AGCM) and oceanic general circulation model (OGCM). Atmospheric and cceanic general circulation models (AOGCMs) represent the pinnacle of complexity in climate models and internalize as many processes as possible. These models include representations of the atmosphere, oceans, biosphere, and polar regions [14].

The way a climate model responds to changes in external forcing, such as an increase in anthropogenic GHGs, is characterized by two standard measures [15]: (1) "equilibrium climate sensitivity" (the equilibrium change in global surface temperature following a doubling of the atmospheric equivalent CO_2 concentration) and (2) "transient climate response" (the change in global surface temperature in a global coupled climate model in a 1% per year CO_2 increase experiment at the time of atmospheric CO_2 doubling). The first measure provides an indication of feedbacks mainly residing not only in the atmospheric model but also in the land surface and sea ice components, and the latter quantifies the response of the fully coupled climate system including the aspects of transient ocean heat uptake [15]. These two measures have become standard for quantifying how an AOGCM will react to more complicate forcing in scenario simulations [6].

An example of AOGCMs is the HadCM3 model. The HadCM3 developed at the Hadley Centre for Climate Prediction and Research, United Kingdom, is considered significantly more sophisticated than earlier versions [15–17]. HadCM3 has a spatial resolution of 2.50° × 3.75° (latitude × longitude), provides information about climate change over the entire world for three times slices: 2020s, 2050s, and 2080s during the twenty-first century. The HadCM3 climate variables are monthly precipitation, solar radiation, and minimum and maximum temperatures. In this model, A2 and B2 climate change scenarios (briefly described below) consider a rise in global annual mean temperature by 3.1°C and 2.2°C, respectively, CO_2 concentration 834 and 601 mg/L, respectively, and global mean sea level rise 52 and 62 cm, respectively. As the resolution of the model is too broad, simple interpolation techniques are applied to fit the specific station site.

In order to increase the reliability and regional specificity of climate change models and to assess future vulnerability to climate change, baseline observational data are used to represent present day GHG emissions and then make projections of future GHG emissions. These projections are then added to the current weather file to develop climate change scenarios. Climate change scenarios incorporate estimates of future population levels, economic activity, governance structure, social values, and patterns of technological change. The IPCC has defined four climate change scenarios (A1, A2, B1, B2) [6].

The A2 climate change scenario depicts a world of regional self-reliance and preservation of local culture. In A2, fertility patterns across regions converge slowly, leading to a steadily increasing population and per capita economic growth, and technological change is slower and more fragmented than for the other storylines. The B2 scenario places emphasis on local solutions to economic, social, and environmental sustainability. The population increases more slowly than that in A2. The economic development is intermediate and less rapid, and technological change is more diverse [18].

The AGCMs were introduced in Egypt 1992 and several studies have been reported since 1992 [9, 19–29]. The HadCM3 climate model and climate change scenarios A2 and B2 are used for studies reported in this chapter. The data for these scenarios are widely available and have received the most scientific peer reviews.

3 Crop Simulation Model

Crop simulation models can assess the likely impact of climate change on grain yield and yield variability. Crop simulation models can predict several key crop characteristics over a wide range of climatic conditions, such as timing of flowering and physiological maturity, through correct descriptions of phenological responses to temperature and day length. Furthermore, accumulation of yield needs to be predicted by accurately predicting the development and loss of leaf area and, therefore, a crop's ability to intercept radiation, accumulate biomass, and partition it to harvestable parts such as grain. Crop water use is also need to be accurately predicted by correctly predicting evapotranspiration and the extraction of soil water by plant root [30].

We used the CropSyst model to study the effects of cropping management systems on crop productivity and the environment under different climate change scenarios. The CropSyst model allows using set of daily weather data spanning on a reasonable number of years to assess the impact of climate change on crops [31–33]. It is a multi-year, multi-crop, daily time step crop growth simulation model, developed with an emphasis on a user-friendly interface, and with a link to GIS software and a weather generator.

Required input files to run the CropSyst model include crop file, soil file, location file, and management file. The values of the crop input parameters were either taken from the CropSyst manual [34] or set to the values observed in the field experiments (described later). The date of each phenological stage from each experiment was used to calculate growing degree days for that stage. Maximum leaf area index was used in the crop file. Soil physical analysis and soil moisture contents measured in each experiment were used to prepare soil file. The location file contains site description. Weather file needed to run the model consisted of precipitation, maximum and minimum temperature, and solar radiation. All these parameters were collected from each experiment for the growing season of the selected crop. An irrigation management file was prepared to represent each treatment in each selected experiment.

The CropSyst model was calibrated for the selected crops (wheat and maize). The calibration consisted of slight adjustments of selected crop input parameters to reflect reasonable simulations. These adjustments were around values that were either typical for the crop species or known from previous experiences with the model. After all input files were prepared, the model was run and the predicted values; total biomass, grain yield, total and seasonal evapotranspiration were compared to the measured values from field experiments. Goodness of fit between measured and predicted values was tested by percent difference between measured and predicted values for seeds and biological yield, and water consumptive use in each growing season, in addition to the root mean squared error (RMSE) according to Jamieson et al. [35]. Furthermore, Willmott index of agreement was calculated, which is a value between 0.0 and 1.0; where 1.0 means perfect fit [36]. The developed climate change scenarios were incorporated in the CropSyst model by removing the weather file measured in the field and replacing it with the future weather file, i.e. climate change [37].

In our studies wheat and maize are used to investigate the effects of climate change and adaptation strategies. Wheat is Egypt's major staple crop and supplies more than one third of the daily caloric intake and 45% of total daily protein consumption of consumers. Wheat is planted as a winter crop and occupies about 33% of the total winter crop area in Egypt. Wheat cultivars used in our studies are Sakha 93, Sakha 94, Giza 168, and Gemiza 9. Maize is planted as a summer crop and is important to the national economy, both as a source of human food and as livestock and poultry feed. Maize production in Egypt has significantly increased

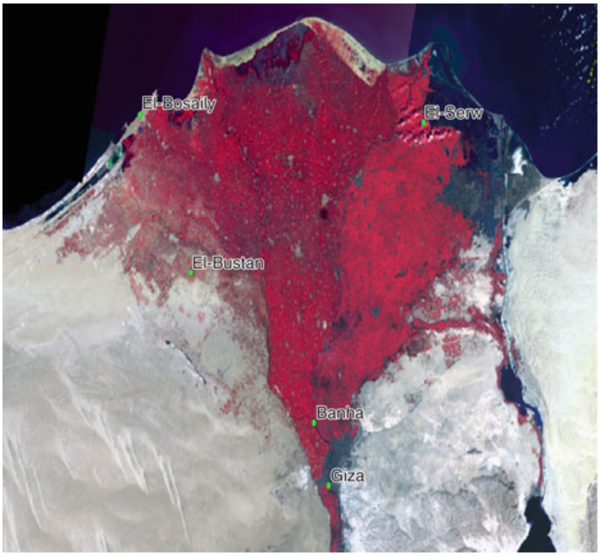

Fig 1 Location of the case study sites in Egypt's four governorates

over the past three decades, from 6.7 to 9.4 ton/ha. Maize hybrids used in our studies are SC10, SC128, TWC310, and TWC323. Wheat-maize rotation is a favorite of Egyptian farmers due to its high profitability.

4 Effects of Climate Change and Adaptation Strategies

Understanding the potential impacts of climate change is very important in developing adaptation strategies and actions to reduce climate change risks. In this chapter, we highlight the potential of using a global climate change model and climate change scenarios to quantify the risk of climate change on wheat and maize production and adaptation strategies in Egypt.

In this section, results from a series of field experiments obtained from case study sites in four governorates in Egypt are compared to results from A2 and B2 climate change scenarios. These four governorates (Fig. 1) are from north to south: Domiatte (located on the Mediterranean Sea in North Egypt), El-Behira (located in the North of the Nile Delta), El-Kalubia (located in the South of the Nile Delta), and El-Giza (located in Middle Egypt). These four governorates are characterized by diverse soil properties.

Results for climate change impact on wheat and maize are summarized below for four governorates.

Table 1 Description of the selected experiments for wheat

Site name	Coordinates	Governorate	Soil type	Irrigation type	References
El-Serw	31.49° N, 31.25° E	Demiatte	Salt affected	Surface	[41, 68]
El-Bustan	30.25° N, 31.02° E	El-Behira	Sandy soil	Sprinkler	[65]
El-Bustan	30.25° N, 31.02° E	El-Behira	Sandy soil	Sprinkler	[54]
El-Bosily	30.29° N, 31.05° E	El-Behira	Clay soil	Sprinkler	[55]
Banha	31.1° N, 30.28° E	El-Kalubia	Clay soil	Surface	[57]
El-Giza	31.13° N, 30.02° E	El-Giza	Clay soil	Surface	[66]
El-Giza	31.13° N, 30.02° E	El-Giza	Clay soil	Sprinkler	[55]

4.1 Wheat Experiments

Table 1 presents the details of seven field experiments that were implemented in four Governorates for four wheat cultivars: Sakha 93, Sakha 94, Giza 168, and Gemiza 9. Sakha 93 is a high yielding cultivar and it is salinity tolerant. Sakha 94, Gemiza 9, and Giza 168 are similar to Sakha 93 in high yielding trait, in addition to being resistant to rust.

4.1.1 Demiatte Governorate

Growing wheat in salt affected soils of El-Serw, Demiatt governorate is a common practice. Wheat grain yield is highly dependent upon the number of spike-bearing tillers produced by each plant and the number of productive tillers depends on the environmental conditions presented during tiller bud initiation and subsequent development stages [38]. Environmental stress during tiller emergence can inhibit their formation and, at later stages, can cause their abortion. Numerous studies have shown that tiller appearance, abortion, or both are affected by salt stress [39, 40]. Soil salinity decreases grain yield of wheat more when plants are stressed prior to booting than when stressed later. The yield component affected most by salt stress is the number of spikes produced per plant [39, 40].

Three irrigation treatments were applied on wheat cultivar Saka 93: (1) traditional farmer irrigation (flood irrigation, characterized by large water application), (2) irrigation amount based on wheat water requirement, i.e. ETc., which refers to the amount of water the crop needs to complete its life cycle to produce maximum yield, and (3) irrigation amount applied to wheat grown on raised bed. The applied irrigation water for these practices was 605, 571, and 487 mm, respectively.

Results, averaged over two seasons, indicate that farmer irrigation increases wheat production vulnerability to climate change, where the average values of yield losses were between 44% and 50% under A2 climate change scenario, and between 41% and 46% under B2 climate change scenario, with the lowest water productivity. Lower yield losses, compared to farmer irrigation, were obtained when wheat was irrigated by required amount in both growing seasons.

Furthermore, the irrigation amount applied for raised bed resulted in even lower yield losses, with the highest water productivity as a result of better growing environment for wheat plants [41].

4.1.2 El-Behira Governorate

At this site wheat was grown on sandy soils and clay soils to determine the effects of agricultural management practices and climate change scenarios on wheat yield. Results are summarized below.

Sandy Soils

The effect of using improved agricultural management practices, i.e. fertigation treatment on wheat cultivar Sakha 93 grown in sandy soil was tested in two field experiments. The aim of these experiments was to determine whether these practices will reduce the vulnerability of wheat to the aboitic stress of climate change. Eight fertigation treatments (interaction between irrigation with 0.6, 0.8, 1.0 and 1.2 of ETc., and fertilizer application in 60% and 80% of irrigation time), in addition to farmer irrigation method were tested. Results show that the highest yield reduction, i.e. 39% and 37% was obtained under A2 and B2 climate change scenarios, respectively, for farmer irrigation. The lowest yield reduction was obtained under irrigation with 1.0 of ETc. and fertigation application in 80% of irrigation time, i.e. 27 and 24% under A2 and B2 climate change scenarios, respectively.

A second experiment was performed at the same site and same cultivar (Sakha 93) to compare the effect of farmer's application of field chemicals (broadcasting fertilizers, insecticide and herbicide on the soil) and chemigation (application of field chemical via irrigation water) on yield losses under A2 and B2 climate change scenarios. Moreover, the effect of the interaction between each treatment and two early sowing dates was simulated to develop effective adaptation strategy to reduce climate change risk on wheat yield grown on sandy soil. Results show that under the two climate change scenarios, wheat grain was reduced by average of 30% under farmer chemical application and by an average of 25% under chemigation. Results also revealed that sowing wheat 1 week earlier under chemigation treatment improved wheat yield by an average of 6% and 5% under A2 and B2 scenarios, respectively.

Clay Soils

Four wheat cultivars, i.e. Sakha 94, Sakha 93, Giza 168, and Gemmiza 9 were used in experiments. Each cultivar was planted in three sowing dates: 9th of November, 24th of November, and 8th of December. Wheat was grown under sprinkler irrigation in four irrigation treatments, i.e. irrigation with 0.6, 0.8, 1.0, and 1.2 of ETc. Results show that the highest reduction in wheat yield was obtained under A2 climate change scenario for all cultivars and under the three sowing dates. The results also revealed that irrigation with 0.6 of ETc. gave the highest yield reduction, and irrigation with 1.2 of ETc. gave the lowest yield reduction for all cultivars and under both climate change scenarios. Furthermore, yield losses of four cultivars were lower when wheat was planted on the 24th of November, compared with the other two sowing dates. Sakha 93 was found to be more tolerant to the aboitic stress of climate change, compared with the three other cultivars under the two climate change scenarios. The reduction in Sakha 93 yield, when planted on the 24th of November, was 21% and 18% under A2 and B2 climate change scenarios, respectively.

4.1.3 El-Kalubia Governorate

Two wheat cultivars, i.e. Giza 168 and Sakha 93 were grown on clay soil under surface irrigation. Under each climate change scenario, the effect of four sowing dates, four irrigations schedules and the interaction between them was simulated. Sakha 93 was found to be more tolerant to climate change than Giza 168, where yield losses were 35% and 41% under A2 and B2 scenarios, respectively. The best adaptation strategy under A2 and B2 climate change scenario was sowing wheat during the 1st week of November and applying second irrigation 4 weeks after sowing and then every 30 days.

4.1.4 El-Giza Governorate

The effects of two irrigation management methods, i.e., surface irrigation and sprinkler irrigation were investigated.

Surface Irrigation

The effect of climate change on the yield of three wheat varieties (Sids1, Sakha 93, and Giza 168) grown under surface irrigation on clay soil and under A2 and B2 climate change scenarios was tested. The effect of two early sowing dates and the effect of a new irrigation schedule on wheat yield were simulated and used as adaptation options. These early sowing dates were 21st of October and 1st of November.

Results show that for both climate change scenarios, Sakha 93 variety was more tolerant to heat stress, where yield losses were 45% and 38% under A2 and B2 scenarios, respectively. It was indicated that wheat yield improvement and irrigation water saving could be attained using the proposed adaptation strategies. Under cultivation on November 1, a slight improvement in yield losses could be achieved with a slight increase in the amount of applied irrigation water, whereas, under sowing on October 21st, a decrease in yield losses could be achieved with a decrease in the amount of applied irrigation water.

Sprinkler Irrigation

Four wheat cultivars, i.e. Sakha 94, Sakha 93, Giza 168, and Gemmiza 9 were grown on silt clay soil. Each cultivar was planted in three sowing dates: 9th of November, 24th of November, and 8th of December. Wheat was planted under sprinkler irrigation in four irrigation treatments, i.e. irrigation with 0.6, 0.8, 1.0, and 1.2 of ETc.

Results reveal that irrigation with 0.6 of ETc. gave the highest yield reduction and irrigation with 1.2 of ETc. gave the lowest yield reduction for all the cultivars and under the both climate change scenarios. Furthermore, yield losses of the four cultivars were lower when wheat was planted on the 24th of November, compared with the other two sowing date. Sakha 93 was found to be more tolerant to the aboitic stress of climate change, compared with the three other cultivars under the three sowing dates and the two climate change scenarios. The reduction in its yield when it planted on the 24th of November was 39% and 34% under A2 and B2 climate change scenarios, respectively.

4.1.5 Discussion

The comparative study between the studied wheat cultivars in the previous experiments revealed that Sakha 93 could attain yield stability traits under the stressful conditions of climate change. Furthermore, in these experiments, Sakha 93 shows a high water productivity value under both current climate and climate change conditions. Therefore, it is important to develop database to classify the available wheat cultivars according to their ability to tolerate abiotic stress such as, heat, and water stresses. In addition, it is important to document how efficient these cultivars are when irrigating water under climate change conditions.

Figure 2 shows wheat yield reduction under climate change condition as affected by soil type. Results indicate that the highest percentage of yield reduction will be occurring for wheat grown on salt affected soil. Results also show that high percentage of yield reduction took place in El-Giza. El-Giza is located in middle Egypt, where temperature is higher than Demiatte Governorate by 2.2°C. These results indicate that soil type is a detrimental factor under high temperature condition. Figure 2 also show that reduction in wheat yield as a result of climate change was lower at El-Behira Governorate compared to other three locations, although soil is sandy in two sites out of the three in this Governorate. Furthermore, yield losses were lower for wheat grown on silty clay soil site, compared to wheat grown on sandy soil.

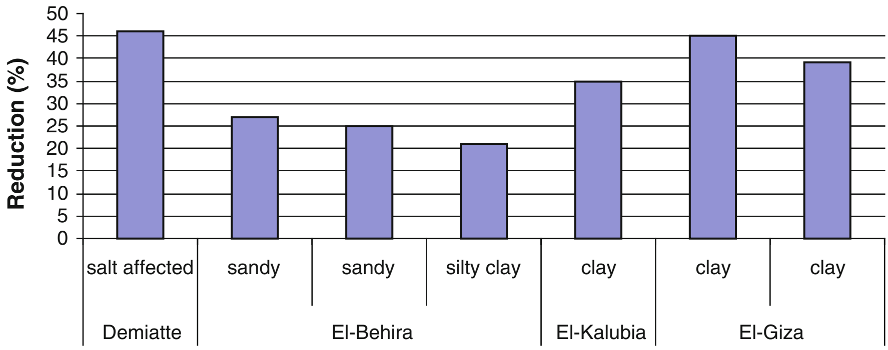

Fig. 2 Percentage of wheat yield reduction under climate change as affected by soil type

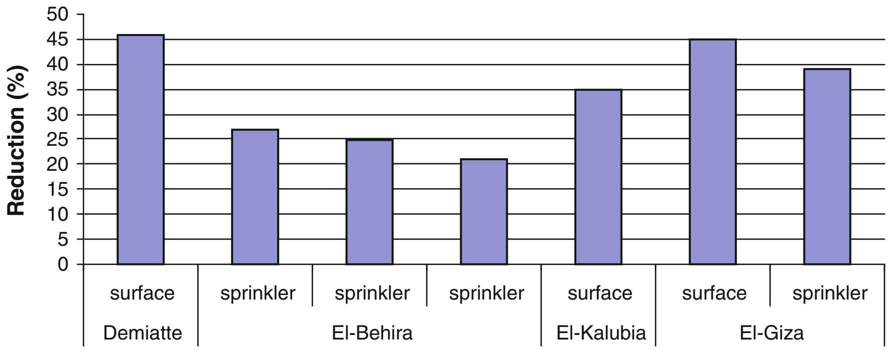

Fig. 3 Percentage of wheat yield reduction under climate change as affected by irrigation system

Results of this study indicate that soil type plays an important role in yield losses under climate change conditions. Therefore, the impact of climate change on soils needs to be considered in parallel with impacts caused by various land-management practices. However, in many cases, it is impossible to separate the effects of these impacts; often they interact, leading to a greater cumulative effect on soils than would be predicted from a simple summation of their effects [42].

Figure 3 shows wheat yield reduction under climate change as affected by irrigation system. Figure 3 suggests that yield losses are lower for wheat grown under sprinkler irrigation in El-Behira governorate, which located in North Nile Delta. Furthermore, in El-Giza governorate yield losses were reduced under sprinkler irrigation. This result implies that sprinkler irrigation can be used as an adaptation strategy to reduce climate change risks on wheat. Table 2 shows measured wheat grain yield under current climate and predicted yield under climate change.

The high reduction in wheat yield under climate change conditions could be attributed to heat and water stresses that wheat plants are exposed to. High temperature reduces numbers of tillers [43] and spikelet initiation and development rates [44].

Table 2 Measured wheat grain yield and predicted yield under climate change

Site name	Measured yield under current climate (ton/ha)	Predicted yield under climate change (ton/ha)	Percentage difference
Demiatte	5.06	2.73	46
El-Behira	6.70	4.89	27
El-Behira	6.16	4.62	25
El-Behira	6.43	5.08	21
El-Kalubia	6.92	4.50	35
El-Giza	5.92	3.26	45
El-Giza	5.86	3.57	39
El-Giza	5.06	2.73	46

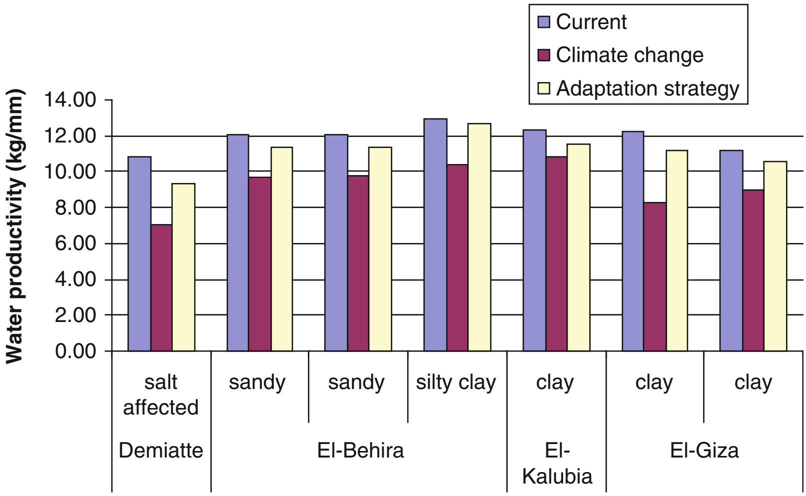

Fig. 4 Wheat water productivity under current climate, climate change, and after using adaptation strategies as affected by soil type

Furthermore, high temperature during anthesis causes pollen sterility [45] and reduces the number of kernels per head, if it prevailed during early spike development [46]. The duration of grain filling is also reduced under heat stress [47], as well as growth rates with a net effect of lower final kernel weight [48, 49].

Furthermore, exposing wheat plants to high moisture stress depress seasonal consumptive use and grain yield [48, 50]. During vegetative growth, phyllochron decreases in wheat under water stress [44] and leaves become smaller, which could reduce leaf area index [51] and reduce the number of reproductive tillers, contributing to reduced grain yield [52]. Furthermore, water stress occurs during grain growth could have a sever effect on final yield compared with stress occurred during other stages [53].

Under climate change scenarios, water productivity was highly reduced in all wheat experiments, compared to current climate conditions (Fig. 4). The deterioration in water productivity was high in salt affected soil, in sandy soil cultivation at

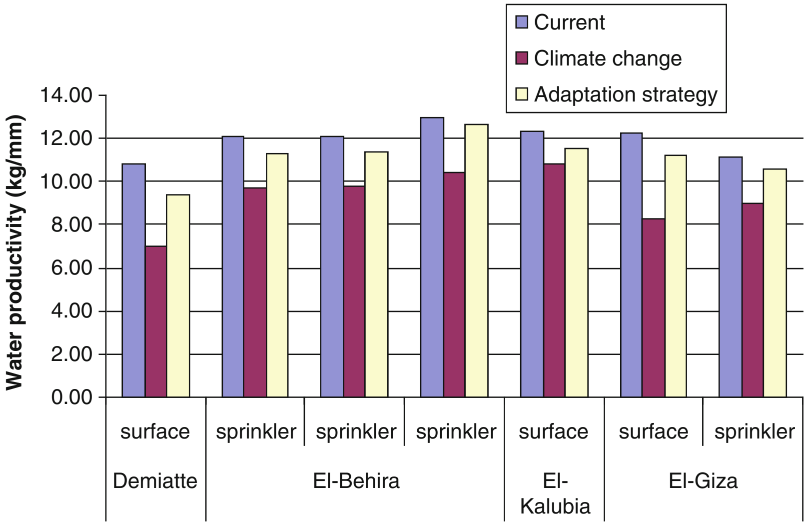

Fig. 5 Wheat water productivity under current climate, climate change, and after using adaptation strategies as affected by irrigation system

Table 3 Description of the selected experiments for maize

Site name	Coordinates	Governorate	Soil type	Irrigation type	References
El-Bustan	30.25° N, 31.02° E	El-Behira	Sandy soil	Drip	[54]
El-Bosily	30.29° N, 31.05° E	El-Behira	Clay soil	Drip	[55]
El-Giza	31.13° N, 30.02° E	El-Giza	Clay soil	Surface	[56]
El-Giza	31.13° N, 30.02° E	El-Giza	Clay soil	Surface	[57]
El-Giza	31.13° N, 30.02° E	El-Giza	Clay soil	Surface	[55]
Banha	31.1° N, 30.28° E	El-Kalubia	Clay soil	Surface	[57]

El-Behira and under surface irrigation at El-Giza. The use of adaptation strategies in all the previous experiments (either simulated or applied in the field) improved water productivity for wheat (Fig. 4).

However, the effect on water productivity was more pronounced under sprinkler irrigation, compared to surface irrigation (Fig. 5). This result shows that sprinkler irrigation could play an important role in reducing climate change risks on wheat, compared to surface irrigation.

4.2 *Maize Experiments*

Table 3 shows characteristics of maize field experiments. Five experiments were implemented in three Governorates: El-Behira, El-Kalubia and El-Giza. CropSyst model was used to simulate maize grain yield under A2 and B2 climate change scenarios. Four maize hybrids were used in these experiments, i.e. SC10, SC128, TWC310 and TWC323. SC10 and SC128 are single cross hybrids, whereas TWC310 and TWC323 are three way cross hybrids.

4.2.1 El-Behira Governorate

Experiments were conducted on sandy soils and clay soils to investigate the effects of agricultural management practices under climate change conditions.

Sandy Soils

The effect of using improved agricultural management practices, i.e. fertigation treatment on maize hybrid SC10 grown in sandy soil was tested in two field experiments. Eight fertigation treatments, in addition to farmer irrigation were tested (interaction between irrigation with 0.6, 0.8, 1.0 and 1.2 of ETc. and fertigation application in 60% and 80% of irrigation time).

Results show that the highest yield reductions, i.e. 43% and 41% were observed under A2 and B2 climate change scenarios, respectively, for farmer irrigation. The lowest yield reductions were obtained under irrigation with 1.2 of ETc. and fertigation application in 80% of irrigation time, i.e. 38% and 35% under A2 and B2 climate change scenarios, respectively [54].

Clay Soils

Four maize hybrids, i.e. SC10, SC128, TWC310, and TWC323 were used in field experiments. These four hybrids were planted in three sowing dates: May 2nd, May 13th, and June 1st. Maize was planted under drip irrigation with four irrigation treatments, i.e. irrigation amount with 0.6, 0.8, 1.0, and 1.2 of ETc.

Results show that for all hybrids under both climate change scenarios, irrigation with 0.6 of ETc. resulted in the highest yield reduction while irrigation with 1.2 of ETc. resulted in the lowest yield reduction. Yield loss was dependent on hybrid type and sowing date. Furthermore, yield losses of all four hybrids were lower when maize was planted on the 2nd of May, compared with the other two sowing dates. The hybrid SC128 was found more tolerant to the aboitic stress of climate change, compared with the three other hybrids under the three sowing dates and the two climate change scenarios. The reduction in SC128 yield, when planted on May 2nd was 28% and 25% under A2 and B2 climate change scenarios, respectively [55].

4.2.2 El-Kalubia Governorate

Two maize hybrids, i.e. TWC310 and TWC324 were grown on clay soil under surface irrigation. Under each climate change scenario, the effect of four sowing dates and four irrigations schedules (Applying 1st irrigation the 3rd week after sowing and then every 10 days, applying 1st irrigation the 3rd week after sowing and then every 12 days; applying 1st irrigation the 3rd week after sowing and then every 8 days, applying 1st irrigation the 3rd week after sowing and then every 16 days) on yield was assessed. The hybrid TWC324 was found to be more tolerant than TWC310, with yield losses of 55% and 49% under A2 and B2 scenarios, respectively.

The best simulated adaptation strategy was found to be sowing maize during the 1st week of May and applying the second irrigation 21 days after sowing and then every 16 days until the end of the growing season [57].

4.2.3 El-Giza Governorate

Two irrigation management techniques, i.e., surface irrigation and drip irrigation were investigated.

Surface Irrigation

The effect of climate change on the yield of two maize hybrids, i.e. TWC310 and TWC324 grown in clay soil under surface irrigation was studied. Under each climate change scenario, the effect of one early sowing date, two irrigations schedules, and the interaction between them was assessed on yield.

The hybrid TWC324 was found to be more tolerant than TWC310, where yield losses were 56% and 50% under A2 and B2 scenarios, respectively. The best simulated adaptation strategy was found to be early sowing and applying irrigation every 14 days [56].

Drip Irrigation

Four maize hybrids, i.e. SC10, SC128, TWC310, and TWC323, were planted in three sowing dates: on the 2nd of May, on the 13th of May, and 1st of June. Maize was planted under drip irrigation with four irrigation treatments, i.e. irrigation amount with 0.6, 0.8, 1.0, and 1.2 of ETc.

Results show that irrigation with 0.6 of ETc. resulted in highest yield reduction and irrigation with 1.2 of ETc. resulted in lowest yield reduction for all the hybrids and under the both climate change scenarios. Furthermore, yield losses of the four hybrids were lower when maize was planted on 2nd of May, compared with the

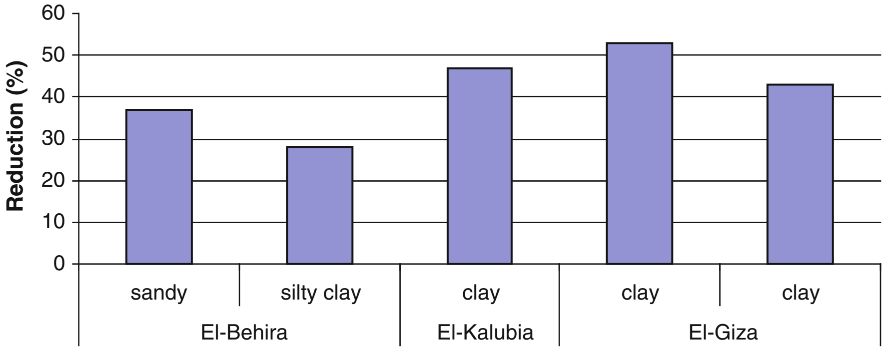

Fig. 6 Percentage of maize yield reduction under climate change as affected by soil type

other two sowing dates. The hybrid SC10 was found to be more tolerant to the aboitic stress of climate change, compared with the three other hybrids under the three sowing dates and the two climate change scenarios. Reductions in maize yield when planted on those sowing dates were 44% and 41% under A2 and B2 climate change scenarios, respectively [55].

4.2.4 Discussion

Results reveal that two maize hybrids (SC10 and SC128) were tolerant to stress under climate change, which implies that these hybrids have traits of yield stability under the variability of climate. This stability is also reflected by lower deterioration in maize water productivity under the stress caused by climate change.

Figures 6 and 7 demonstrate the effect of soil type and irrigation systems on maize yield losses under two climate change scenarios. Using drip irrigation on silty clay soil reduced yield losses, compared with its value under sandy soil in El-Behira Governorate (North Nile Delta). The reduction in yield was higher at El-Kalubia (maize grown on clay soil under surface irrigation). The highest yield reduction was observed in El-Giza, Middle Egypt. However, maize grown under drip irrigation result in less yield losses, compared to maize grown under surface irrigation, 42% under drip irrigation versus 52% under surface irrigation. Table 4 shows measured maize grain yield under current climate and predicted yield under climate change for drip irrigation.

Under climate change conditions, maize production could adversely be affected due to heat stress which can accelerate the rate of maize plant growth [58]. Furthermore, high temperature can reduce kernel sink capacity and limit subsequent kernel development and final maize yield, and it has been suggested that each 1°C increase in temperature above optimum could result in a reduction of 3–4% in maize grain yield [59, 60]. During the early stage of kernel development,

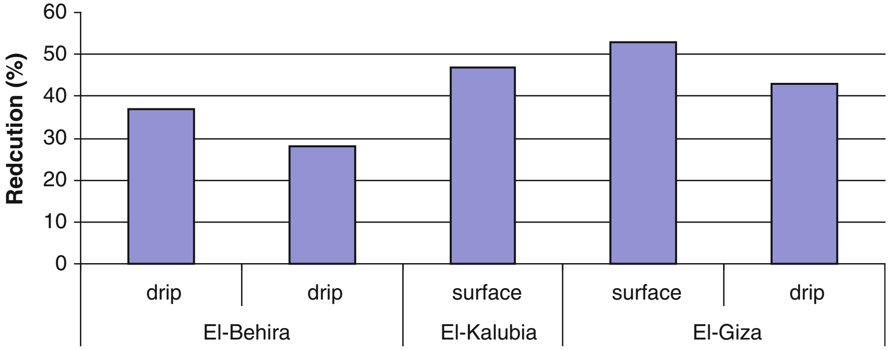

Fig. 7 Percentage of maize yield reduction under climate change as affected by irrigation system

Table 4 Measured maize grain yield and predicted yield under climate change – drip irrigation

Site name	Measured yield under current climate (ton/ha)	Predicted yield under climate change (ton/ha)	Percentage of difference
El-Behira	6.88	4.33	37
El-Behira	7.28	5.24	28
El-Giza	8.33	4.41	47
El-Giza	8.92	4.19	53
El-Giza	8.73	4.98	43

heat stress is particularly detrimental to subsequent dry matter accumulation, since it disrupts cell division, sugar metabolism, and starch biosynthesis in the endosperm [61].

Climate change also causes water stress. Water stress during maize growing season reduces plant height, leaf area index, and total leaf area [62, 63]. In addition, number of ovules that fertilize and develop into grains decreases rapidly when drought occurs during flowering [64]. Moreover, both maize yield and kernel number are reduced as a result of water stress during grain filling period [58].

Similar to wheat, water productivity was highly reduced under climate change scenarios, compared to current climate conditions. The highest percentage of reduction in water productivity was found when maize was planted in sandy soil at El-Behira and under surface irrigation at El-Giza. Maize water productivity was improved when adaptation strategies was used in all the previous experiments, either simulated or applied in the field (Fig. 8).

Furthermore, the effect of using adaptation strategies was more noticeable under drip irrigation, compared with surface irrigation (Fig. 9). Result show that using drip irrigation for maize production could be important in reducing climate change risks.

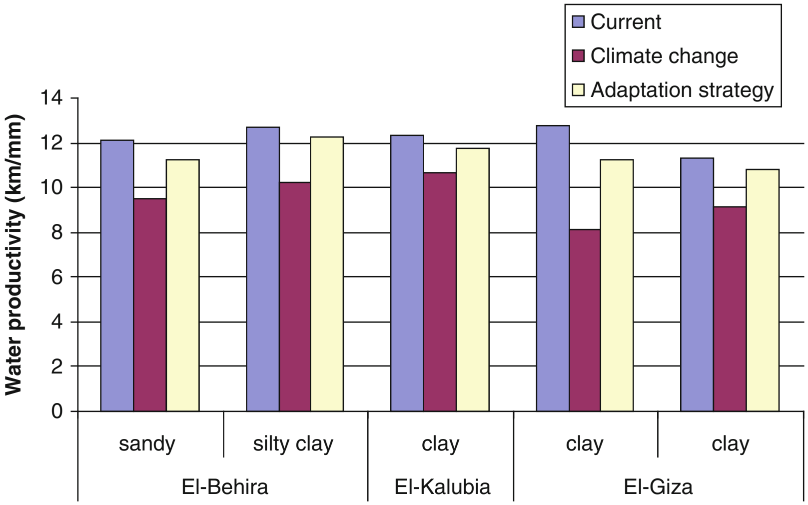

Fig. 8 Maize water productivity under current climate, climate change, and after using adaptation strategies as affected by soil type

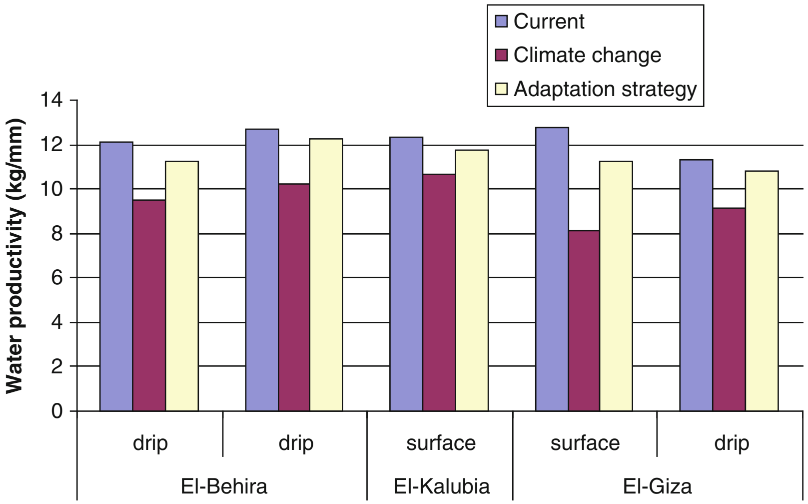

Fig. 9 Maize water productivity under current climate, climate change, and after using adaptation strategies as affected by soil type

5 Conclusions

Assessing the possible impact of climate change on production risks is necessary to help decision makers and stakeholders identify and implement suitable measures of adaptation [8]. Sustainable land and water management combined with innovative agricultural technologies could mitigate climate change and help farmers adapt to its impacts. Thus, climate change impacts needs to be assessed at the farm level, so that farmers can be involved in research and development activities [65].

New knowledge, technology, and policy for agriculture have never been more critical, and adaptation and mitigation strategies must urgently be applied to national and regional development programs. Without these measures the world and particularly developing countries will suffer from decreased food security. The positive effects of adaptation strategies on agriculture under climate change have been confirmed in many studies [41, 66–68]. The best way to adapt to uncertain future climate is to improve adaptation to present day climate variability and reduce vulnerability to extreme events.

Results of simulation models can help crop breeders develop new crop varieties adaptable to climate change. Study results show that wheat and maize breeders will need to focus on overcoming heat stress rather than improving drought tolerance as a result of climate change. Moreover, breeding for crop varieties with higher water use efficiency should be another important goal. Under climate change, achieving greater water use efficiency is the primary challenge for agricultural scientists. Appropriate irrigation scheduling methods could provide efficient irrigation management techniques to alleviate adverse effects of climate change. The real challenge under climate change conditions is to use adaptation strategies, i.e., improved agricultural management practices, to reduce the potential damage of climate change on crop yield. Furthermore, developing optimum nitrogen fertilizer regime could help in reducing the adverse effect of climate change on crops yield, and it may also help in conserving irrigation water. Thus, simulation models can be the ultimate solution for testing all these options.

Acknowledgments The authors would like to express their gratitude to all fellow researchers who provided the data required to complete this chapter.

References

1. IPCC (1996) Impacts, adaptation and mitigation of climate change: scientific technical analyses. Cambridge University Press, Cambridge, p 831
2. Jones PD, Moberg A (2003) Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. J Clim 16:206–223
3. IPCC (2001) Summary for policymakers: climate change 2001: the scientific basis, contribution of working group I to the 3rd assessment report of the intergovernmental panel on climate change Houghton JT, Ding Y, Griggs DJ, Noguer M, Van Der Linden PJ, and Xioaosu D. Cambridge University Press, Cambridge, p 944
4. Alexander L, Zhang X, Peterson TC (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res Atmos 111:D05109
5. Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nystrom M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J (2003) Climate change, human pacts, and the resilience of coral reefs. Science 301:929–933

6. IPCC Report (2007) The fourth assessment report (AR4). http://www.ipcc.ch/. Accessed 14 March 2007
7. Rosenzweig C, Hillel D (1998) Climate change and the global harvest. Oxford University Press, New York
8. Torriani DS, Calanca P, Schmid S, Beniston M, Fuhrer J (2007) Potential effects of changes in mean climate and climate variability on the yield of winter and spring crops in Switzerland. Clim Res 34:59–69
9. Eid HM, El-Marsafawy SM, Ainer NG (2002) Using MAGICC and SCENGEN models in vulnerability and adaptation to climate change studies. Metrol Res Bull 16:23–26, Jan. Egypt. 12–19
10. Parry M, Arnell N, Hulme M, Nicholls R, Livermore M (1998) Adapting to the inevitable. Nature 395:741
11. Carter TR (1996) Assessing climate change adaptations: the IPCC guidelines. In: Smith JB et al (eds) Adapting to climate change: an international perspective. Springer, New York, pp 27–43
12. FAO (2003) Unlocking the water potential of agriculture. FAO Corporate Document Repository, Rome, Italy, 260 pp
13. Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. Geophys Res Lett 33:L01602
14. Vinnikov KY, Grody NC, Robock A, Stouffer RJ, Jones PD, Goldberg MD (2006) Temperature trends at the surface and in the troposphere. J Geophys Res 111:D03106
15. Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parameterization in the Hadley Centre Climate Model-HadCM3. Clim Dyn 16:123–146
16. Gordon C, Cooper C, Senior CA, Banks H, Gregory HJM, Johns TC, Mitchell JFB Wood RA (2000) The simulation of sea surface temperature, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim Dyn (16):147–168
17. Hulme M, Jenkins GJ (1998) Climate change scenarios for the UK: Scientific Report. UKCIP Technical Report No.1. Climate Research Unit, Norwich
18. Hennessy K (2006) Climate change scenarios for initial assessment of risk in accordance with risk management guidance. CSIRO, Australia
19. Eid HM, Ainer NG, Yousef KMR, Ibrahim MAM, Gad El-Rab GM (1992a) Climate change crop modeling study on wheat. In: 5th Egyptian botany conference, Siant Cather, Sinai, pp 113–130
20. Eid HM, Ainer NG, Yousef KMR, Sherif MA, Miseha WI, El-Sergany DZ (1992b) Climate change crop modeling study on maize. In: 5th Egyptian botany conference, Siant Cather, Sinai, pp 93–111
21. Eid HM, El-Sergany DZ (1993) Impact of climate change on soybean yield and water needs. In: Proceeding first conference on the environment, Egypt, pp 313–316
22. Eid HM (1994) Impact of climate change on simulated wheat and maize yields in Egypt. In: Rosenzweig C, Iglesias A (eds) Implications of climate change for international agriculture: crop modeling study. US Environmental Protection Agency, Washington, pp 57–70
23. Eid HM, El-Sergany DZ, McCuistion WL (1994a) Simulated soybean yield and water requirements in relation to selected agronomic characters in Egypt. In: Proceeding of sixth conference in agronomy, Al-Azhar University, vol II, pp 471–489
24. Eid HM, Anton NA, Tarrad AM (1994) Comparative study on Egyptian wheat cultivars and their response to high temperatures. Ann Agric Sci Moshtohor 32(1):143–154
25. Eid HM, El-Marsafawy SM, Ainer NG, Ali MA, Shahin MM, El-Mowelhi NM, El-Kholi O (1996) Vulnerability and adaptation to climate change in Egyptian agriculture. Country study report. CSP, Washington, pp 1–53
26. Eid HM, El-Marsafawy SM, Ainer NG, El- Mowelhi NM, El-Kholi O (1997a) Vulnerability and adaptation to climate change in maize crop. In: Meteorology and environmental cases conference, Egypt, 2–6 March 1997, pp 332–340

27. Eid HM, El-Marsafawy SM, Shahin MM, Khater AN, Abdel Gelil I (1997b) Adaptation of Egyptian cotton crop to climate change. In: Meteorology and environmental cases conference, Egypt, 2–6 March 1997, pp 340–345
28. Eid HM, El-Mowelhi NM (1998) Impact of climate change on field crops and water needs in Egypt. In: African international environmental conference, Egypt, 2–4 October 1998, pp 234–238
29. Hassanein MK, Medany MA (2007) The impact of climate change on production of maize (*Zea mays* L.). In: International conference on climatic changes and their impacts on coastal zones and river deltas: vulnerability, mitigation and adaptation, Alexandria, Egypt, 23–25 April 2007, pp 271–288
30. Richter GM, Semenov MA (2005) Modeling impacts of climate change on wheat yields in England and Wales: assessing drought risks. Agric Syst 84(1):77–97
31. Stockle CO, Martin S, Campbell GS (1994) CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. Agric Syst 46:335–359
32. Tubiello FN, Donatelli M, Rosenzweig C, Stockle CO (2000) Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian sites. Eur J Argon 13:179–189
33. Torriani D, Calanca P, Lips M, Ammann H, Beniston M, Fuhrer J (2007) Regional assessment of climate change impacts on maize productivity and associated production risk in Switzerland. Reg Environ Change 16:23–29
34. Stockle CO, Nelson R (1994) Cropping systems simulation: model users manual (version 10200). Biological Systems Engineering Department, Washington State University, Washington, p 167
35. Jamieson PD, Porter JR, Goudriaan J, Ritchie JT, van Keulen H, Stol W (1998) A comparison of the models AFRCWHEAT2, CERES-Wheat, Sirius, SUCROS2 and SWHEAT with measurements from wheat grown under drought. Field Crops Res 55:23–44
36. Willmott CJ (1981) On the validation of models. Phys Geogr 2:184–194
37. El Afandi G, Ouda SA, Khalil FA, Ewias M (2010) Using CropSyst model to predict barley yield under climate change conditions in Egypt: II. Simulation of the effect rescheduling irrigation on barley yield. Afr J Plant Sci Biotechnol (SI):6–10
38. Nerson H (1980) Effects of population density and number of ears on wheat yield and its components. Field Crop Res 3:225–234
39. Maas EV, Grieve CM (1990) Spike and leaf development in salt-stressed wheat. Crop Sci 30:1309–1313
40. Nicolas ME, Mums R, Samarakoon AB, Gifford RM (1993) Elevated CO_2 improves the growth of wheat under salinity. Aust J Plant Physiol 20:349–360
41. Ouda SA, Abdraboh M, Noreldin T (2012a) Combating the harm effect of climate change on wheat using irrigation water management. In: 4th field crops conference, Cairo, Egypt, 28–31 August 2012
42. Brinkman R, Sombroek WG (1993) The effects of global change on soil conditions in relation to plant growth and food production. In: Expert consultation paper on "Global climate change and agricultural production: direct and indirect effects of changing hydrological, soil and plant physiological processes." FAO, Rome, 16 pp
43. Friend DJC (1965) Ear length and spikelets number of wheat grown at different temperatures and light intensities. Can J Bot 43:343–353
44. McMaster GS (1997) Phenology, development, and growth of wheat (*Triticum aestivum* L.) shoot apex: a review. Adv Agron 59:63–118
45. Saini HS, Aspinall D (1982) Sterility in wheat (*Triticum aestivum* L.) Induced by water stress or high temperature: possible mediation by abscisic acid. Aust J Plant Physiol 9:529–537
46. Kolderup I (1979) Application of different temperatures in three growth phases of wheat. II. Effects on ear size and seed setting. Acta Agric 29:11–116
47. Sofield IL, Evans T, Wardlaw IF (1977) The effect of temperature and light on grain filling in wheat. Agric Bull 12:909–915

48. Bagga AK, Rawson IM (1977) Contracting responses of morphologically similar wheat varieties to temperature appropriate to warm temperature climates with hot summers: a study in controlled environment. Aust J Agric Res 40:965–980
49. El-Kalla SE, Leilah AA, Basiony AH, Hussien SM (1994) Effect of Irrigation and foliar nutrition treatments on growth and yield of some wheat cultivars under El Arish area condition. In: 6th conference of agronomy. Faculty agriculture, Al-Azhar University, Egypt
50. Khater AN, Abdel Maksoud HH, Eid HM (1997) Response of some wheat cultivars and their water relations to different irrigation level in Middle Delta. Egypt. J Appl Sci 11(2):15–29
51. Gardner FP, Pearce RB, Mitchell RL (1985) Physiology of crop plants. Iowa State University Press, Ames
52. Mosaad MG, Ortiz-Ferrara G, Mahalak-Shmi V (1995) Tiller development and contribution to yield under different moisture regimes in two Triticum species. J Agron 174:173–180
53. Hanson AD, Nelson EC (1980) The biology of crop production. Academic, New York
54. Taha A (2012) Effect of climate change on maize and wheat grown under fertigation treatments in newly reclaimed soil. PhD thesis, Tanta University, Egypt
55. Abd Rabouh M (2011) Water management for some field crops grown under climate change conditions: a project report. Scientific Technology Development Fund, Egypt
56. Ouda SA, Khalil FA, Yousef H (2009) Using adaptation strategies to increase water use efficiency for maize under climate change conditions. In: 13th conference on water technology, Hurghada, 12–15 March 2009
57. Moneer I (2012) Simulation of the effect of adaptation strategies on improving yield of some crops grown under expected climate change conditions. MSc thesis, Institute of Environmental Research Studies, Ain Shams University, Egypt
58. Ritchie SW, Hanway JJ, Benson GO (1993) How corn plant develops. Iowa State University Science Technology. Cooperative Extension Services. Report No. 48. Iowa State University, Ames
59. Cheikh N, Jones RJ (1994) Disruption of maize kernel growth and development by heat stress: the role of cytokinin/abscisic acid balance. Plant Physiol 166:45–51
60. Shaw RH (1983) Estimates of yield reductions in corn caused by water and temperature stress. In: Rupert CD Jr, Kramer PJ (eds) Crop relations to water and temperature stress in humid temperate climates. Westview Press, Boulder, pp 49–66
61. Monjardino P, Smith AG, Jones RJ (2005) Heat stress effects on protein accumulation of maize endosperm. Crop Sci 45(4):1203–1210
62. Cassel DK, Martin CK, Lambert JR (1985) Corn irrigation scheduling in humid regions on sandy soil with tillage pans. Agron J 77(6):851–855
63. El-Shenawy AA (1990) Effect of water stress and plant population on single and double crosses in maize (*Zea mays* L.). M.Sc. thesis, Faculty of Agricultural. Kafr El Skeikh, Tanta University, Egypt
64. Gomma MA (1981) Effect of plant population, nitrogen levels and water stress on two maize cultivars. Ann Agric Sci Moshtohor 23(2):233–330
65. Jones PG, Thornton PK (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environ Change 13:51–59
66. Khalil FA, Farag H, El Afandi G, Ouda SA (2009) Vulnerability and adaptation of wheat to climate change in Middle Egypt. In: 13th conference on water technology, Hurghada, 12–15 March 2009
67. Ouda SA, Sayed M, El Afandi G, Khalil FA (2010) Developing an adaptation strategy to reduce climate change risks on wheat grown in sandy soil in Egypt. In: 10th international conference on development of dry lands, Cairo, 12–15 December 2010
68. Ouda SA, Noreldin T, Abou El-Enein R, Abd El-Baky H (2012b) Improved agricultural management practices reduced wheat vulnerably to climate change in salt affected soils. In: 4th field crops conference, Cairo, 28–31 August 2012

Grain Production Trends in Russia, Ukraine, and Kazakhstan in the Context of the Global Climate Variability and Change

Elena Lioubimtseva, Kirsten M. de Beurs, and Geoffrey M. Henebry

Abstract Russia, Ukraine, and Kazakhstan are the three major grain producers in Central Eurasia. In the context of the current food-price crisis, these countries might be presented with a window of opportunity to reemerge as the major grain exporters if they succeed in increasing their productivity. Global grain production is highly sensitive to a combination of internal and external factors, such as institutional changes, land-use changes, climate variability, water resources, and global economic trends. Agroecological scenarios driven by climate models suggest that land suitability in this region is likely to change in future, due to impacts of climate change, such as CO_2 fertilization, changes in the growing season, temperature, precipitation, frequency, and timing of droughts and frosts. Grain production in Russia, Ukraine, and Kazakhstan grew steadily between 2002 and 2010 following a 10-year long depression caused by collapse of the USSR. However, in the summer of 2010 Russia and its neighbors experienced an unprecedented heat wave, accompanied by severe wild fires. As news of this disaster became known international grain prices increased dramatically. The future of grain production in this region will be determined by the interplay of climatic variability and multiple non-climatic factors and is likely to have significant impact on both global and regional food security over the coming decades.

E. Lioubimtseva (✉)
Geography and Planning Department, Grand Valley State University, 1 Campus Drive, Mackinac Hall B-4-202, Allendale, MI 49401, USA
e-mail: lioubime@gvsu.edu

K.M. de Beurs
Department of Geography and Environmental Sustainability, The University of Oklahoma, 100 East Boyd St., SEC Suite 566, Norman, OK 73019, USA

G.M. Henebry
Geographic Information Science Center of Excellence (GIScCE), South Dakota State University, 1021 Medary Ave., Wecota Hall 506B, Brookings, SD 57007, USA

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 121–142, DOI 10.1007/698_2013_225,

Keywords Climate change, Drought, Food security, Globalization, Heat wave, Kazakhstan, Land use, Russia, Ukraine, Water resources

Contents

1 Introduction

The current global food crisis clearly indicates that the world's food balance and agricultural livelihoods are highly vulnerable to economic instability and climatic variability. Global grain stocks and prices in 2000–2012 have been particularly volatile as a complex result of political, economic, and environmental factors, including shifting allocation of grain production towards biofuel, increasing global oil prices, changes in food consumption patterns in Asia, and the disruption of food production due to poor harvests in Europe and Australia [1], and massive withdrawal of arable lands in the newly independent countries of the former USSR [2–5]. With abundant highly fertile but under-utilized lands the grain-growing countries of the former USSR, such as Russia, Ukraine, and Kazakhstan, have an opportunity to take a lead on the global market and become top beneficiaries of this rapidly changing food-production landscape if they manage to increase their productivity.

Since collapse of the USSR in 1991, the agricultural systems of Russia, Ukraine, and Kazakhstan have undergone enormous institutional changes that have resulted in exclusion of approximately 23 million hectares of arable lands from production, 90% of which had been used for grain [5, 6]. This land-use transition was the largest withdrawal of arable lands in recent history [4, 7, 8]. The major factors of change in the 1990s were the disintegration of the centrally planned institutions in the agricultural sector and uncertainties in the legal status of land, which resulted in declines in agricultural subsidies, use of technology, and access to markets [9]. In turn, these forces precipitated significant declines of both cereal areas and grain productivity that bottomed out across the region around year 2000 [10–15]. Although the decline of grain production in Russia, Ukraine, and Kazakhstan was followed by slow recovery in 2000–2010, the productivity remains low as a result of combination of economic and environmental factors. In 2010 the wheat productivity was 2.6 t/ha in Ukraine, 1.9 t/ha in Russia, and 0.7 t/ha in Kazakhstan (compared to 7.0 t/ha in France, 4.7 t/ha in China, 3.1 t/ha in the United States) [16]. In summer 2010 the European part of Russia was hit by an extraordinary heat wave with the highest July temperatures since at least 1880 and numerous locations setting all-time maximum temperature records [17]. The heat wave and extreme drought also affected Ukraine, Belarus, and northern Kazakhstan, wildfires swept through some agricultural areas and severely damaged crops. The Russian government declared a state of emergency in 27 agricultural regions, 43 regions had been affected, and over 53 million acres of crops destroyed [18]. The 2010 heat wave cut grain yield in Russia by a third, the potato harvest by 25%, and vegetables by 6% [16, 18]. The Volga region – the biggest grain producer in Russia – was most severely hit by the drought, with an annual harvest drop of more than 70%, while the Central region harvest dropped by 54%. Prices for the staple crop increased about 50% [19]. Although the 2011–2012 summer temperatures in this region were not as high as during the 2010 heat wave, persistent droughts continued during the following 3 years through the entire grain-producing semiarid belt of Eurasia. The heat wave and drought impacted grain markets not only in Russia, Ukraine, and Kazakhstan but the entire world. First, as soon as it became clear that the Eurasian grain harvest was going to be severely affected by the drought, international grain prices increased dramatically [18, 19]. Second, in response to this increase, and in an effort to protect local consumers and local meat producers, the Russian government instituted a grain export ban that pushed grain prices even higher in the international markets.

To date, only a few studies have examined the determinants and the scale of grain production trends and volatility in the Former Soviet Union countries. The goal of this chapter is to examine the interplay of climate variability and other key factors that have determined the recent dynamics and trends of grain production in this region.

2 Factors Affecting Food Production

Food security and the associated risks of disruption to production and distribution networks depend on multiple biogeophysical, sociocultural, political, and economic factors. These can include the respective sensitivities of the agricultural sector to climatic variability, water resources, global market variations, country-scale political, institutional, and economic changes, local policies, and other factors.

2.1 Impacts of Climate Change

Agricultural production and export opportunities are highly sensitive to interannual climate variability as expressed in growing season weather. Climate change and increasing climate variability are likely to bring changes in land suitability and crop yields. Atmosphere-Ocean General Circulation Models (AOGCMs) predict that the temperature in the grain-producing areas of Central Eurasia will increase by

1.5–3.5°C by 2030–2050, with the greatest increase in winter [20]. Despite significant differences in the range of changes among the scenarios produced by different models, the majority of models tend to agree that summer precipitation is likely to decline all over the region and winter precipitation is projected to increase in parts of European Russia and Siberia [3, 4]. The models disagree about the range and pattern of precipitation changes. Lioubimtseva and Henebry [5] used MAGICC/SCENGEN 5.3.2 model [21] to analyze regional climate change scenarios projected by 20 different AOGCMs described in the IPCC Fourth Report [20]. All AOGCMs predict that under any policy scenario, maximum temperatures are likely to increase by 2050 both in summer and in winter; increases of the mean and maximum summer temperatures in combination with mean precipitation decreases, and droughts may become more likely [3].

Climate change projections indicate both increasing risks and opportunities for Russia and its neighbors. A number of food security studies have employed the AOGCM projections and FAO agroecological zoning (AEZ) combined with the IIASA (International Institute for Applied System Analysis) Basic Link Combination (BSL) economic models [22–25]. The scenarios based on the IIASA AEZ–BSL approach indicate that Russia, Ukraine, and Kazakhstan might be among the greatest beneficiaries of expansion of suitable croplands due to increasing winter temperatures, a longer frost-free season, CO_2 fertilization effect, and projected increases in water-use efficiency by agricultural crops, and possible, though uncertain, increases in winter precipitation projected by some AOGCMs [24].

The IIASA BSL models driven by the HadCM3-A1FI scenario suggest that, due to the regional climate changes by 2080, the total area with agroecological constraints could decrease and the potential for rain-fed cultivation of major food crops could increase in Russia due to changing regional climate (primarily due to temperature increase and the CO_2 fertilization effect on C_3 plants). Pegov et al. [26] estimated that grain production in Russia may double due to a northward shift of agricultural zones. A study by Mendelsohn et al. [27] based on the Global Impact Model experiments that combined AOGCM scenarios, economic data, and climate-response functions by market sector suggested that a 2°C temperature increase could bring Russia agricultural benefits of US$124–351 billion, due to a combination of increased winter temperatures, extension of the growing season, and CO_2 fertilization (Table 1).

Other modeling studies, however, indicate that the predicted shift of agroecological zones is unlikely to result in increasing agricultural productivity. Dronin and Kirilenko [3] and Alcamo et al. [28] have shown that although large portions of Russia might increase their agricultural potential under warming scenarios, agriculture of the most productive chernozem zone in the Russia and Ukraine, area between the Black and the Caspian Seas, could experience a dramatic increase in drought frequency. These regions are the main commercial producers of wheat and any decline in productivity would be detrimental to exports [5].

Golubev and Dronin [29] have developed an integrated model “GLASS”, which provide a consistent method for examining changes in agricultural production and water supply in the Russian Federation as a result of global climate change. As a

Table 1 Climate and agroecological scenarios from climate and agroecological modeling experiments

Study	Experiment	Scenario summary
Fischer et al. [24]	FAO agroecological zoning (AEZ) combined with the IIASA Basic Link Combination (BSL) economic models	Total area with agroecological constraints will decrease, the potential for rain-fed cultivation of major food crops will increase due to temperature increase and the CO_2 fertilization effect
Pegov et al. [26]	FAO agroecological zoning (AEZ) combined with the IIASA Basic Link Combination (BSL) economic models	Significant increase of grain production due to a northward shift of agroecological zones
Mendelsohn et al. [27]	Global Impact Ricardian Model-combined AOGCM scenarios, economic data, and climate-response functions by market sector	A 2°C temperature increase can bring agricultural benefits of US $124–351 billion, due to a combination of increased winter temperatures, extension of the growing season, and CO_2 fertilization
Alcamo et al. [28]	The Global Assessment of Security (GLASS) model (containing the Global AgroEcological Zones (GAEZ) crop production model and the Water-Global Assessment and Prognosis (WaterGAP 2) water resources model)	Increase in average water availability in Russia, but also a significantly increased frequency of high runoff events in much of central Russia, and more frequent low runoff events in the already dry crop growing regions in the South. The increasing frequency of extreme climate events will pose an increasing threat to the security food system and water resources
Dronin and Kirilenko [3]	Adapted the GAEZ and WaterGap2 model	Temperature and precipitation increase throughout Russia, precipitation decline and increase of drought frequency in the key grain-producing regions, net decline of grain production
Golubev and Dronin [29]	GLASS model examining changes in agricultural production and water supply as a result of global climate change	Production increase in the more humid central and northern regions. The net average yield in Russia will decrease considerably due to a severe increase in droughts in the most productive regions

consequence of climate change, the GLASS model predicts a considerable decrease of cereal yields in the most productive parts of Russia. Even though cereals will grow in the more humid central and northern regions, the average yield in Russia will decrease considerably due to a severe increase in droughts in the most productive regions. In Stavropolsky Krai, the key agricultural region of the Northern Caucasus, potential cereal production would decrease by 27% in the 2020s and by 56% in the 2070s. In contrast, the yield of cereals in the Central region will not change much, whereas yields in the northern regions will increase significantly. However, this latter increase contributes little to the total grain production of the country (Table 1).

Global and regional climate models agree that the major grain-producing regions of the semiarid belt of Southern Russia, Ukraine, and Kazakhstan are likely to experience more intense and frequent droughts and the events of summer 2010 are likely to repeat in future more often. A study by Dole et al. [17] explored whether early warning can be issued through knowledge of natural and human-caused climate change. The authors used model simulations and observational data to determine the impact of observed sea surface temperatures (SSTs), sea ice conditions, and greenhouse gas concentrations. Results of model simulations suggest that the heat wave and drought of 2010 were mainly due to internal atmospheric dynamical processes that produced and maintained a strong and long-lived blocking event, and that similar atmospheric patterns have occurred with prior heat waves in this region [17]. The study suggested that neither human influences nor other slowly evolving ocean boundary conditions contributed substantially to the magnitude of this heat wave. Results also provide evidence that such an intense event could be produced through natural variability alone. Based on this modeling experiment, slowly varying boundary conditions that could have provided predictability and the potential for early warning did not appear to play an appreciable role in this event.

2.2 *The Impact of Land Use and Agricultural Practices*

Following the collapse of the USSR at the end of 1991, the period of reforms through the early 2000s was characterized almost everywhere by the following phases in the agricultural sector: (1) loss of subsidies and access to markets, (2) deintensification of agriculture, including reduction of livestock, longer fallow periods, and apparent abandonment of marginal croplands, (3) reduction in crop yields, (4) conversion of marginal arable lands to pastures, and (5) localized deforestation due to increasing demand for firewood [5, 12, 30, 31].

The crop yields declined during the 1990s in each country as the high price of imported herbicides, fungicides, and insecticides caused farmers to cut back on their use. Fertilizer use fell by 85% in Russia and Ukraine and by almost 90% in Kazakhstan between 1990 and 2000; the grain production fell by more than 50% during the same period of time [16]. The loss of state subsidies following the collapse of the Soviet Union in 1991 also increased feed and production costs and reduced profitability for livestock enterprises. As prices for meat products increased, consumer demand declined, thus establishing a downward spiral that continued throughout the decade. Livestock inventories and demand for forage continued to shrink. Russia lost almost half of its meat production between 1992 and 2006: (1) the number of cattle dropped from almost 20 to 10.3 million heads,

(b) the number of pigs fell from more than 36.3 to 18.7 million, and (3) the number of sheep dropped from 20 to 7 million [16]. Similar trends occurred in Kazakhstan and to a lesser extent in Ukraine [5].

The increasing inability of large agricultural enterprises to maintain livestock operations, due largely to inefficient management and farms' inability to secure adequate supplies of feed, resulted in increased dependence on private producers and household farms to satisfy demands for meat [18]. Furthermore, the involvement of investor groups in agricultural production has had an impact on livestock numbers. Many farmers, who entered agreements with investment firms, killed off their herds because livestock was not quickly profitable and not as attractive to investors. For example, in Kazakhstan, due to the loss of incentives to keep the herds, two-thirds of the sheep population were lost between 1995 and 1999 [5]. The drop in livestock inventories led in turn to a drop in demand for feed grain and pastures across the region. Although the free-fall in livestock inventories has slowed since 2000, large industrial farms have been shifting away from livestock and toward crop production [32]. Thus, total livestock inventories have continued to decrease, particularly in the areas with extensive herding, such as Central Asia and semiarid and arid zones of Russia [5, 31]. Although the area cultivated for cereals has overall declined since the disintegration of the Soviet Union, the major crops have shown distinct trajectories (Fig. 1).

Wheat is the primary cereal crop in terms of area harvested and continues to cover significant area in each country. Wheat production shows increases since the early 2000s following a long decline since peak area following the end of the Virgin Lands Program in the early 1960s. Barley has been a significant secondary crop, but declines in area harvested started in the mid-1970s and became precipitous in the mid-1990s. Rye and oats are largely restricted to Russia and have declined substantially since 1991 and show no evidence of recovery. Maize continues to be a minor crop regionally, but the harvested area has been increasing steadily in Ukraine and Russia since the mid-1990s.

Steady recovery of crop production observed between 2002 and 2009 and followed by a sharp decline in 2010 was due to the unprecedented heat wave, crop failures, and fires affecting this region [17]. Due to recovery of some agricultural subsidies and at least a partial success of reforms, fertilizer and machinery use has increased during the past few years. The use of mineral fertilizer has tripled since 1999 in Kazakhstan and doubled in Russia and Ukraine, but current application rates represent only a fraction of the amounts applied in the late 1980s [16]; however, a return to the 1980s application rates is neither likely nor desirable as they were frequently above recommended levels. Another important technological factor contributing to the apparent improvement in Kazakhstan grain yield is the increase in the use of certified planting seed. By 2004, the use of certified seed had increased to 94%, including an increase in the use of top-quality certified seed from 37% to 57% [33].

Crop yields in Ukraine have shown a long-term increasing trend with a substantial deviation following 1991 and a return to higher yields in later years (Fig. 2). Yields in Russia have continued a slow but steadily increase over the past half

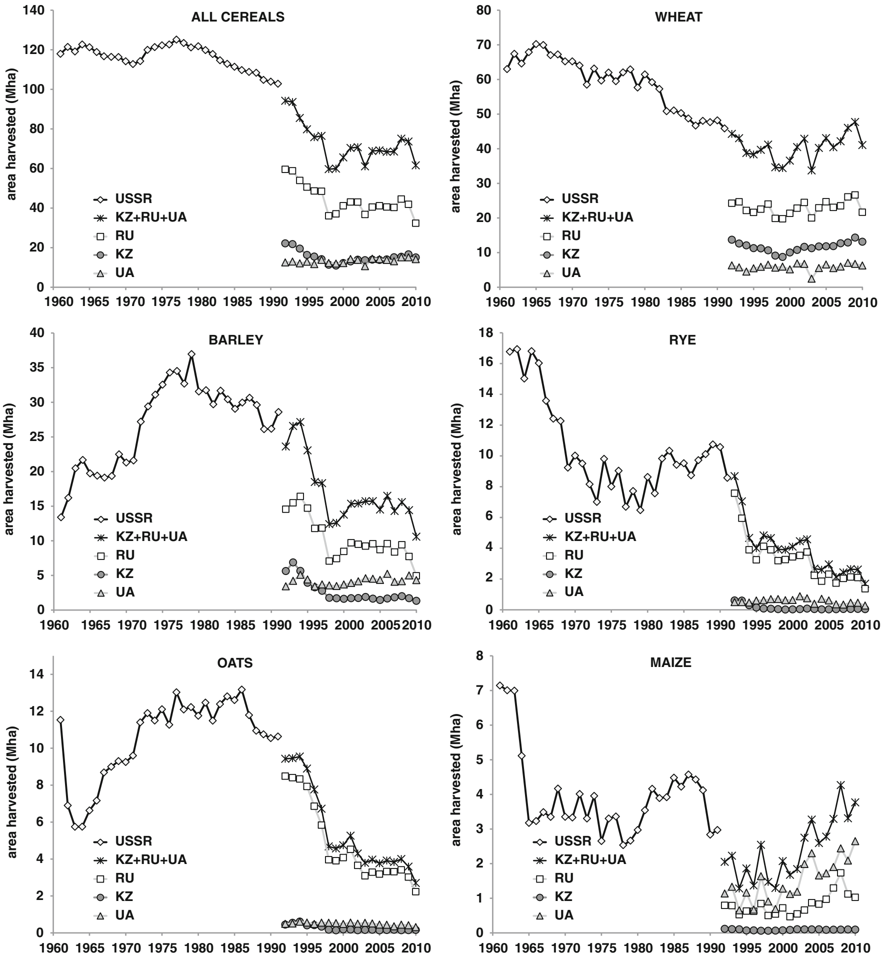

Fig. 1 Areas harvested for major cereals crops in the USSR, Russian Federation, Kazakhstan, and Ukraine (Source: FAOSTAT [16])

century despite some set-backs in the 1990s. Yields in Kazakhstan have shown little improvement over half a century, though recent yields have been mostly better than during the late 1990s. However, the impacts of extreme heat wave years – 2003 and 2010 – are evident in the yield data: Ukraine was more affected in 2003, while Kazakhstan was more affected in 2010, with Russian yields dropping in both years (Fig. 2).

While agricultural statistics provide critical information about land-use dynamics, remote sensing offers a complementary perspective on land change. Remote sensing based land cover classification products from 2003 through 2010 reveal relatively little apparent change in the chernozem (black earth) region of Ukraine, Russia, and Kazakhstan at a spatial resolution of 0.05° (Fig. 3). The variational land

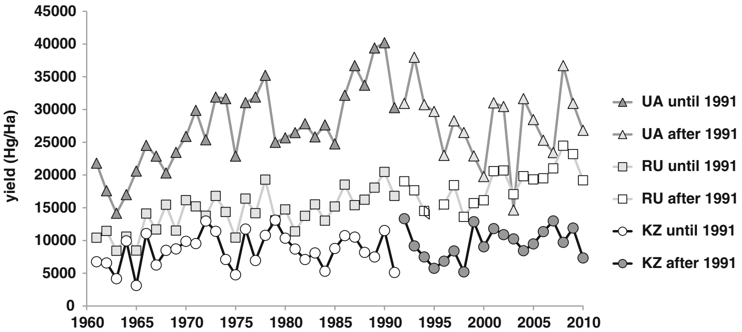

Fig. 2 Wheat yields from Russia, Kazakhstan, and Ukraine during and after the Soviet era (Source: FAOSTAT [16])

cover analysis in Fig. 3 highlights degrees of temporal stability in land cover and reveals the gradual ecotone between cropland and grassland at the southern limit of the chernozem. Post-classification change analysis, in which areal changes across categories are quantified, shows differences at local and trans-boundary scales [6]. However, it is very difficult to parse what land cover changes arise from changes in land use rather than from disturbance or even methodological instability [34].

Land surface phenology studies the timing and magnitude of seasonal patterns in the vegetated surface as observed at spatial resolutions that are very coarse relative to individual plants [12, 35]. In the absence of obscuring clouds, the vegetated land surface is readily viewed from space due to the strong contrast in green plants between the near infrared and red portions of the electromagnetic spectrum. Green plants are very bright in the near infrared, scattering upwards of a third of incident radiation, but very dark in the red, absorbing more than 90% of incoming light. The normalized difference vegetation index (NDVI) exploits this spectral contrast.

Time series of NDVI data provide important windows onto land surface phenology and land change dynamics. Studies comparing the land surface phenologies before and after the collapse of the Soviet Union found significant differences that appeared as an "earlier onset of spring" were attributable to the deintensification of agriculture [12, 36]. However, land surface phenologies are also responsive to climatic variability and change as well as growing season weather. In the chernozem region land surface phenologies are influenced by the Northern Annular Mode, evident through the North Atlantic Oscillation and the Arctic Oscillation indices [37].

Analysis of significant changes in the temporal pattern of NDVI over the longer term reveals the impacts of broader scale disturbances like drought (Fig. 4). Applying this approach at two scales enables extensive changes in northern Kazakhstan due to weather and climate to be distinguished from localized changes in southern Russia due to human land-use decisions [38].

Recent analyses of the agricultural conditions in the grain belt have found strong divergence between areas within and outside of the chernozem zone. The

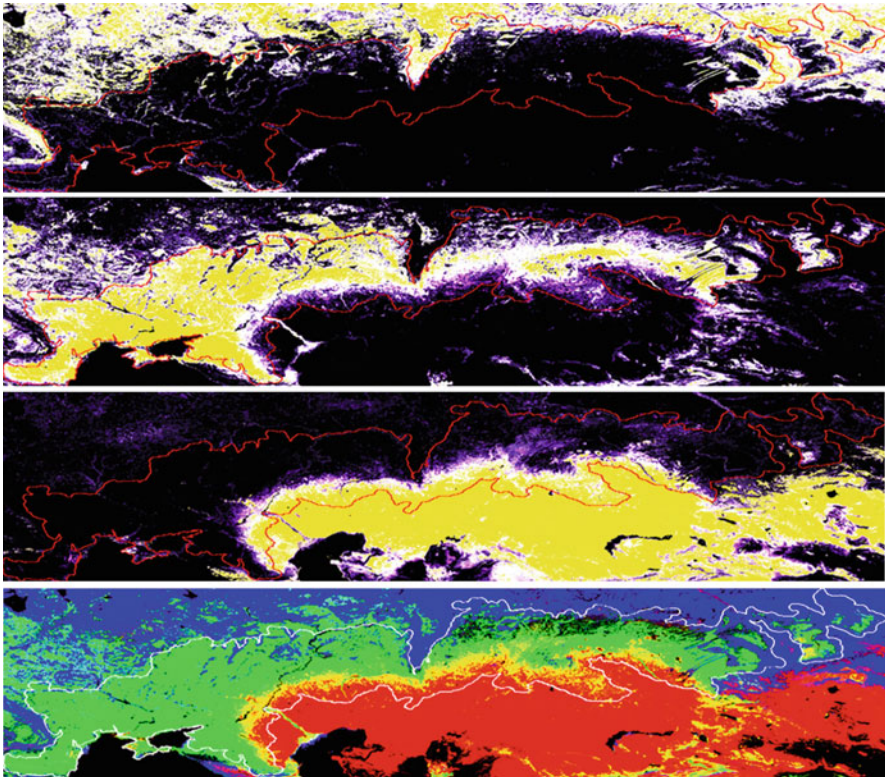

Fig. 3 Temporal stability of major land cover types in the black earth (chernozem) region 2003–2010. (*Top*) False color composite displays maximum, average, and range of percent IGBP land cover class from MODIS 0.05° product. *Black* indicates absence of class; *yellow* denotes stable core area; *white* shows unstable core; *magentas* are unstable but persistent periphery; and *blues* are erratic periphery. *Top three panels* show mixed forest, cropland, and grassland classes, respectively. *Bottom panel* shows maximum percentages for the three classes (*red* = grassland, *green* = cropland, *blue* = mixed forest)

agricultural sector has been disintegrating since at least 1991 outside of the chernozem zone, for example, Kostroma; yet, in the black earth lands agriculture is vigorous and diversifying, for example, Samara [32, 39].

2.3 Changes in Regional and Global Economy

In the Soviet era, agriculture had been supported by budget subsidies and favorable relative prices, and benefitted from fuel and transportation subsidies that were not specific to agriculture but helped farmers more than most other producers. Very

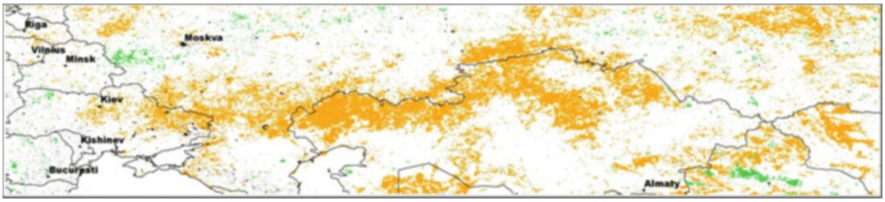

Fig. 4 Significant changes ($p < 0.01$) in the vegetated land surface over the 2001–2010 growing seasons as revealed by the nonparametric Seasonal Kendall test. *Orange* (*green*) indicates a significant negative (positive) change. Data are from MODIS NBAR 16-day composites at 0.05° resolution

abrupt price liberalization of the early 1990s led to an increase in the cost of key inputs that was much larger than the increase in the market value of farm outputs.

The Organization for Economic Cooperation and Development (OECD) producer support estimates for Russia, Ukraine, and Kazakhstan indicate substantial positive support for farmers up to 1991, in which then almost fell to zero in the following few years [40]. Among the three countries, Ukraine had most drastically reduced its agricultural subsidies during the years of transition. Although agricultural subsidies have increased in former-USSR countries in past few years and are now comparable with the US level, they are significantly lower than those in Europe or Japan [5]. According to the FAO, the level of overall support given to agricultural producers as a share of their total farm receipts amounted to 15% and 12%, respectively, in Russia and Ukraine, compared to 33% in the EU, 55% in Japan, and 16% in the USA [16]. Russia declared a national priority area for agriculture in 2005 and increased federal support for agricultural development from US$2.6 billion in 2006 to US$5.2 billion in 2008 [41]; the same tendency is observed in Kazakhstan, and to a lesser extent in Ukraine [41].

One of the more serious problems associated with implementation of agricultural reforms in all three countries has been the lack of long-term support for agricultural reforms by the key stakeholders – the rural population – resulting in weak public and private governance in the agricultural sector. Several studies conducted in this region reveal the lack of public support for the land reform and rather negative public perception of land ownership and the land market [2, 14, 42]. In a study conducted in the Russian countryside, about 90% of the respondents disagreed with a concept of cropland privatization and were against the idea of private land ownership and market [43]. Interviews in several former-USSR countries indicate that food security is generally perceived in this region as one of the key responsibilities of the state and people generally tend to blame poor economic situation and increasing food prices on the failure of the government [44]. There is still negative attitude of the population to the removal of agricultural subsidies and institution of the land market [45]. These attitudes of stakeholders might be the key factor explaining why the three countries have been slow and inconsistent in implementation of their new land codes, and returned to some agricultural policies that are not in line with market orientation [2, 14].

Many national-scale institutional changes in the post-Soviet economies have developed as direct or indirect responses to globalization after the newly independent states emerged from the closed and highly regulated economic spaces of the USSR and Council for Mutual Economic Assistance (COMECON) into the more open and volatile spaces of regional and global markets [5]. Economic globalization has led to liberalization of trade and investment, formation of the regional economic agreements, implementation of structural adjustment programs, and removal of subsidies, tariffs, and price supports [46, 47]. A select group of larger agricultural enterprises in Russia, Ukraine, and Kazakhstan may benefit from economic globalization by focusing on production of export commodities. However, many small to medium size farms in the post-Soviet states are threatened with failure due to removal of subsidies, volatile crop prices, competition with cheaper and/or better quality imports, inability to obtain credit, limited access to international markets, and shortage of inputs, such as high-quality seed, fertilizers, herbicides, machinery, and irrigation [45, 47, 48]. As Leichenko and O'Brien [47] demonstrated in a study on agriculture in southern Africa, farmers must adapt simultaneously to change in climate and in global markets; thus, the vulnerability/resilience of food production to the change must be considered from multiple perspectives.

Globalization brought significant change to the food trade of the post-Soviet states, as per capita incomes in the 1990s fell sharply and the level of inequality increased dramatically. Accordingly, poverty grew more quickly in the transitional economies of the former USSR during the 1990s than in any other part of the world [49]. The standards of living have begun to recover only after 2000. However, as indicated by several assessments and datasets, globalization has never led to deterioration of food security in Russia, Ukraine, and Kazakhstan, despite the deterioration of their agricultural sectors [16, 50, 51].

While agricultural production, livestock inventories, and per capita incomes all have plunged and partially recovered during the past 16 years, anthropometric and dietary indicators show that food consumption in terms of calories remained steady, and indicators of food inadequacy were very moderate [49, 52]. The predominant dietary problems are the same as before independence: namely, a high prevalence of overweightness and obesity, related to very high consumption levels of meat, dairy products and eggs, and low consumption of fruits and vegetables. This condition arose because average food consumption in these countries before 1991 was as high or higher than in developed countries, and far higher than in the developing world. From 1992 to 2000 agricultural production of Russia fell by 29% but per capita caloric consumption did not change [50, 53]. Per capita food consumption fell moderately during the period of reforms – in Ukraine by 15% and by 11–12% in Kazakhstan – but, as a study by Wehrheim and Wiesmann [54] indicates, this reduction reflects a shift away from overconsumption of meat rather than true malnutrition. Still the calorie reduction in the diet of post-Soviet republics is generally seen as a serious threat to the national food security by the local population, politicians, and occasionally by the national scientific community. For example, an article by Baydildina et al. [55] based on the data from the Ministry of Agriculture of Kazakhstan documents reductions in consumption of meat, dairy products, and sugar between 1990 and 1996, but the consumption of fruits, vegetables, potatoes, and grains during the same period remained almost unchanged. The authors interpret these data as an evidence of growing malnutrition in Kazakhstan. For example, milk and dairy product consumption at the end of 1980s was close to 1 kg/day per person in Kazakhstan and dropped by about 30% in 1997 [55]. However, protein and sugar consumption had been excessive during the Soviet period when food prices were kept extremely low.

While the rates of protein consumption in Russia, Kazakhstan, and Ukraine have been comparable to EU levels, the proportion of fruits and vegetables in the diet remains significantly lower than recommended. This problem, however, is cultural: it results from the traditional diets of these countries. During the Soviet years and into the 1990s, consumption of fruits and vegetables was typically much lower in Kazakhstan than in Russia and Ukraine, and it was significantly below western standards in all three republics. Although there is little evidence that globalization has seriously threatened food security in Russia, Ukraine, or Kazakhstan, the popular opinion is that it is indeed threatened [49, 53].

Globalization impacts after independence have led to changes of import and export partners and geography of trade flows. While livestock inventories in the post-Soviet economies declined rapidly during the period of reforms, high levels of consumption of meat and dairy products have been maintained. Russia and Ukraine, previously importers of feed grains, have recently become the major importers of beef, poultry, and dairy products from the US and EU. Meat and dairy product imports have also grown in Kazakhstan. Economic reforms and related land-use changes in Russia, Ukraine, and Kazakhstan have also impacted food security worldwide due to the changes in their trade structure. USSR was an important exporter of grain in the 1960s, but became a major importer of grain in the 1970 and 1980s due to increasing meat consumption and growing need for feed grains to support livestock. During the past few years Russia, Ukraine, and Kazakhstan have been becoming, once again, important players in global grain markets, with geographic proximity to the buyers in the EU countries, Middle East, and Northern Africa, stable export markets and domestic prices showing close correlation with world reference prices [44].

As the cereal production in Russia, Ukraine, and Kazakhstan is projected to increase [33, 41, 56], domestic demands are likely to continue to decline. Populations of Russia and Ukraine are projected to decline and the regional per capita incomes are expected to increase with consumer diets shifting from cereals. With appropriate policies, this combination of rising prices and demand on the international market and decreasing domestic demand is likely to benefit export opportunities in Russia, Ukraine, and Kazakhstan.

Table 2 Grain production scenarios for Russia, Ukraine, and Kazakhstan. Adapted from Lioubimtseva [4]

	Grain production, million metric tons					
				Scenarios for 2016–2017		
Countries	1992–1994	2004–2006	2010	OECD–FAO	IKAR	EBRD maximum potential scenario
Russia	93	77	60	n/a	98	126
Ukraine	37	37	39	n/a	44	75
Kazakhstan	23	14	12	n/a	22	29
Total	152	128	111	159	164	230

Table 3 OECD–FAO projections of the global grain exports in 2016. Adapted from Lioubimtseva [4]

Producer	Share of global grain exports (%)	Cumulative share of global grain exports (%)
USA	34	34
CIS	14	48
EU-27	13	61
Australia	11	72
Canada	9	81
All others	19	100

3 Uncertainties in Future Agricultural Production

Total grain production scenarios for 2016 for Russia, Ukraine, and Kazakhstan together range from 159 to 230 million tons projected by European Bank for Reconstruction and Development (EBRD) "maximum potential scenario" [41]. Table 2 shows grain production scenarios for Russia, Ukraine, and Kazakhstan.

As shown in Table 3, the share of Russia, Ukraine and Kazakhstan in agricultural production is expected to reach 14–15% by 2016 and surpass the share of the EU, Canada, and Australia [40]. These projections, however, are highly uncertain. The "estimated maximum potential" scenario developed is based on assumptions that (1) grain yields in Kazakhstan would be comparable to those in Australia; (2) yields in Russia will be similar to the current yields in Canada; and (3) yields in Ukraine will approach yields in France [41]. These analogies are based on similarities in temperature and precipitation but do not take into account socioeconomic and cultural differences and, therefore, are quite simplistic.

The ERBD–FAO scenario also assumes that 13 million hectares of abandoned land would be returned to production and devoted to grain, and no change in crop distribution was assumed for already cultivated land [41]. As a result, the grain export potential is also likely to increase: wheat export projections for 2016/2017 vary in the assessments by different agencies between 11 and 17 million tons of wheat for Russia [40, 51, 57], and between 6 and 10 million tons for Ukraine [40]. Export of Kazakhstan and other Central Asian states of FSU is projected to approach

4–7 million tons of wheat [40]. Export of coarse grains is also expected to reach about 1–2 million tons in Russia and 6–9 million in Ukraine [33]. The OECD–FAO projected that wheat and coarse grain exports from Russia, Ukraine, and Kazakhstan would reach 35 million tons by 2016 (a 14% increase from 2007) [41].

3.1 Uncertainties Related to Climate and Land Changes

Projections of grain production increase in the countries of the former USSR are based primarily on assumptions of expansion of areas suitable for agriculture and increasing productivity. These assessments are based on modeling changes and geographic shifts of mean temperature and precipitation, but do not take into account how changes in climate variability and extreme events might be detrimental to crop production. Numerous studies have documented that extreme events are disproportionately responsible for weather-related damages and, furthermore, the sensitivity of extreme events to climate change may be greater than simple linear projections of climatological distributions [3, 28, 58]. The potential changes in variability and extreme events – frosts, heat waves, droughts, and deluges – are likely to have stronger impacts on food production than modest temporal shifts in mean temperature and minor changes in precipitation.

The grain productivity projections also do not taken into account possible changes in the land suitability due to impacts of climate change, such as CO_2 fertilization, changes in the growing season, temperature, precipitation, frequency and timing of droughts and frosts. Although several modeling studies have shown that a warmer climate would be beneficial in general for agriculture in Northern Eurasia [22–24, 26], geographic distribution of benefits is unlikely to be uniform. CO_2-enrichment studies in greenhouses, growth chambers, and open-top chambers have suggested that growth of many crops could increase in the short term about 30% on average with a doubling of the atmospheric CO_2 concentration. The results of FACE (free air CO_2 enrichment) experiments, however, suggest that CO_2 fertilization effects may be seriously overestimated by ecological models [59]. When the CO_2 fertilization is not taken into account, the warmer climate benefits for the CIS agriculture are modest at best and production gains due to theoretically possible expansion of arable lands might be lower than the losses caused by increasing aridity [5].

Although the agricultural productivity of non-chernozem zones is expected to increase (particularly in Siberia), it is unrealistic to expect swift adaptation of the agricultural sector to newly emerging agroecological conditions. Any projection of agricultural expansion based on climate change scenarios should be viewed with caution, if they do not take into account regional socioeconomic factors [3, 5]. Expansion of climatic zones suitable for agriculture does not necessarily imply that the local population currently employed in other sectors would seek out new opportunities in agriculture. On the other hand, declining productivity due to increasing aridity may result in the loss of human capital as skilled farmers may be forced to switch to other livelihoods. Assessment of human vulnerability and adaptations to climate change needs to become a key component of agricultural policies. Adaptations, such as introduction of drought-resistant crop varieties and introduction of irrigation into rain-fed croplands, may alleviate some consequences of increasing aridity and variability of climate.

3.2 Policy-Related Uncertainties

Food-production projections assume no drastic institutional changes and continuation of current agricultural policies. However, many former-USSR countries are still in the process of restructuring their agricultural policies. Two other critical variables to increasing grain production and export are the development of credit institutions and the modernization of infrastructure [41, 45, 53]. Renewing existing agricultural machinery and purchasing the new equipment would require large capital investments, but the existing credit system and leasing arrangements limit the flow of capital for investments. According to IKAR, the total investment required for modernization of grain handling systems in Russia, Ukraine, and Kazakhstan would amount to approximately US$4.5 billion [41, 56]. Modernization of transportation networks and port infrastructure in Russia and Ukraine necessary for increasing export capacity would require substantially larger investments.

Changes in the trade policies incorporated in the global and regional food-production scenarios are difficult to project. Such policies may include price controls, quotas, tariffs, subsidies, and interventions using state reserves. In the face of rising international food prices, Russia, Ukraine, and Kazakhstan have already imposed some export restrictions to protect their domestic consumers. The Russian government made several agreements in 2007–2009 with retailers to freeze prices on some basic foodstuffs [56]. Ukraine has been using export quotas on wheat, barley, and maize to ensure sufficient supply of the domestic market [41] and Kazakhstan has introduced licensing measures to control the exports of wheat and also lowered import duties on all basic foodstuffs. While such policies may protect domestic consumers in the short term, they can also harm agricultural producers in the longer term, particularly in the CIS countries where agricultural subsidies are relatively low. By restricting the translation of international prices into the national markets, such policies significantly reduce the profits of domestic agricultural producers and limit opportunities for rural development.

3.3 Uncertainties Related to Global Factors

Climatic variability, extremes, and change can affect food production across the planet. Increasing variability in local and regional climates is likely to increase volatility in the food supply. Other global factors, including the rapidly expanding demand for biofuels, volatility of oil prices, increasing demand for agricultural products in the emerging economies, and changing diets in developing countries, are likely to continue increasing demand for agricultural production. Grain producers in Russia, Ukraine, and Kazakhstan are likely to benefit from this window of opportunity in the global market, only if national policies and international investments support the current trend of increasing productivity and assist in bringing back into production some of the arable lands idled during the transitional decade of the 1990s.

4 Conclusions

Agroecological models driven by climate change scenarios and land change analysis suggest that Russia, Ukraine, and Kazakhstan have a great potential to increase their grain productivity and future exports. A combination of winter temperature increase, extension of the growing season, and CO_2 fertilization could increase water availability and land suitability for agricultural crops. However, projections based on biophysical modeling alone should be considered with caution as they do not take into account regional socioeconomic and political factors. Human adaptations to climate change are likely to take several generations – much longer than the agroecological responses to climate change. Expansion or geographic shifts of climatic zones suitable for agriculture do not necessarily imply that the local population currently employed in other sectors would seek out new opportunities in farming.

During the 1990s and early 2000s, the agricultural systems of this vast region underwent enormous land-use changes accompanied by massive withdrawals of arable land, contraction of livestock inventories, and catastrophic decline of grain production. The decline of agriculture in the FSU countries had little to do with climate change but was a direct result of ineffective agricultural and economy-wide reforms, lack of competition, loss of agricultural subsidies, nonexistent land market, poor infrastructure, and a lack of support by the stakeholders.

It has been projected by several international agencies that within the next decade countries of the former Soviet Union could become the second major grain exporter after the United States and also surpass the European Union. Scenarios based on the climatic analogies and climate change scenarios are quite uncertain, as they do not take into consideration cultural differences, the role of stakeholders, continuous changes in the land code of the CIS region, slow land market development, national financial systems, local infrastructure, and price fluctuations of the international market.

To realize their full potential as the major grain producers, Russia, Ukraine, and Kazakhstan have to overcome many challenges. Underdeveloped land markets remain one of the major unresolved issues. The governmental policies currently clearly favor large agricultural companies, particularly in Russia and Kazakhstan.

Two other critical variables to increasing grain production and export are the development of credit institutions and the modernization of infrastructure. Renewing existing agricultural machinery and purchasing new equipment would require very significant investments, but the existing credit system and the current financial crisis in the FSU (Former Soviet Union) nations and worldwide are likely to limit the flow of capital available for investments.

Development of effective and sustainable food-production strategies in the grain belt of Eurasia requires further basic, applied, and translational research in the following areas: (1) more accurate modeling of climate change and its impacts on water availability and agroecological zones, particularly at the regional scale; (2) synoptic monitoring and stochastic modeling of extreme events, such as droughts, heat waves, wild fires, frosts, and floods; (3) field and chamber experiments to improve understanding of CO_2 fertilization on agricultural crops; (4) synoptic monitoring and simulation modeling impacts of land-use and land cover changes on the regional hydrometeorology and meso-climatic and agroecological changes; (5) research on human adaptations to climate change, such as geographic and economic mobility and behavioral changes, including changes in livelihoods, lifestyles, diets, and cultural practices; and (6) how adaptation measures can be embedded in ongoing activities such as land-use planning, water resource management, drought and heat-wave early warning, and diversification of agriculture.

Finally, due to the cross-scale contingent dynamics of coupled human/natural systems, it is critical to approach the planning, assessment, and implementation of adaptation tactics and strategies at the national, regional, and international levels simultaneously.

Acknowledgments This research was supported in part by the NASA LCLUC program as part of the Northern Eurasia Earth Science Partnership Initiative (NEESPI; http://neespi.org) through projects NNG06GC22G to G.M. Henebry, W.J. Capehart, and E. Lioubimtseva and NNX09AI29G to K.M. de Beurs, G. Ioffe, and G.M. Henebry. We would like to thank P. de Beurs for the application development that allowed us to calculate the Seasonal Kendall tests efficiently.

References

1. Rosset P (2008) Food sovereignty and the contemporary food crisis. Development 51:460–463. doi:10.1057/dev.2008.48
2. Koester U, Brümmer B (2006) Institutional changes for agricultural and rural development in the CEEC and CIS region. Electron J Agric Dev Econ 2(2):144–179
3. Dronin N, Kirilenko A (2008) Climate change and food stress in Russia: what if the market transforms as it did during the past century. Climate Change 86(1–2):123–150
4. Lioubimtseva E (2010) Global food security and grain production trends in Central Eurasia: do models predict a new window of opportunity? Natl Soc Sci J 41(1):154–165
5. Lioubimtseva E, Henebry GM (2012) Grain production trends in Russia, Ukraine and Kazakhstan: new opportunities in increasingly unstable world? Front Earth Sci 6(2):157–166. doi:10.1007/s11707-012-0318-y

6. Wright CK, de Beurs KM, Henebry GM (2012) Combined analysis of land cover change and NDVI trends in the Northern Eurasian grain belt. Front Earth Sci 6(2):177–187. doi:10.1007/s11707-012-0327-x
7. Henebry GM (2009) Carbon in idle croplands. Nature 457:1089–1090
8. Prishchepov AV, Müller D, Dubinin M, Baumann M, Radeloff V (2013) Determinants of agricultural land abandonment in post-Soviet European Russia. Land Use Policy 30:873–884
9. Lerman Z, Sedik D, Pugachev N, Goncharuk A (2007) Rethinking agricultural reform in Ukraine. Leibniz Institute of Agricultural Development in Central and Eastern Europe, vol 38, IAMO, Halle
10. Zhang B (1996) Total factor productivity of grain production in the former Soviet Union. J Comp Econ 24:202–209
11. Meng E, Longmire J, Moldashev A (2000) Kazakhstan's wheat system: priorities, constraints, and future prospects. Food Policy 25(6):701–717
12. de Beurs KM, Henebry GM (2004) Land surface phenology, climatic variation, and institutional change: analyzing agricultural land cover change in Kazakhstan. Remote Sens Environ 89:497–509
13. Muratova N, Terekhov A (2005) A five-year experience of satellite monitoring agricultural crops in Northern Kazakhstan. Опыт пятилетнего оперативного мониторинга сельскохозяйственных угодий Северного Казахстана с помощью спутниковых данных (in Russian). In: Laverov NP (ed) Actual problems in remote sensing of the Earth from space, vol 2. Institute of Space Research of Russian Federation, Moscow, pp 277–283
14. Uzun V (2005) Large and small business in Russian agriculture: adaptation to market. Comp Econ Stud 47:85–100
15. Bokusheva R, Hockmann H (2006) Production risk and technical inefficiency in Russian agriculture. Eur Rev Agric Econ 33(1):93–118. doi:10.1093/erae/jbi036
16. FAOSTAT (2012) Food and Agriculture Organization Statistics. http://www.fao.faostat.org. Accessed July 2012
17. Dole R, Hoerling M, Perlwitz J, Eischeid J, Pegion P, Zhang T, Quan X-W, Xu T, Murray D (2011) Was there a basis for anticipating the 2010 Russian heat wave? Geophys Res Lett 38: L06702. doi:10.1029/2010GL046582
18. Welton G (2011) The impact of Russia's 2010 grain export ban. Oxfam Research Reports. Oxfam, UK. www.oxfam.com/grow
19. USDA FAS (2010) Effects of the summer fires and droughts and Russian agriculture, GAIN report. USDA Foreign Agriculture Service, Washington, p 5
20. IPCC (2007) In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation, contribution of working group III to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge
21. Wigley TML (2008) MAGICC/SCENGEN 5.3: USER MANUAL (version 2), NCAR, Boulder. http://www.cgd.ucar.edu/cas/wigley/magicc/UserMan5.3.v2.pdf. Accessed 14 January 2013
22. Fischer G, Shah M, van Velthuizen H (2002) Climate change and agricultural vulnerability. International Institute for Applied Systems Analysis, Vienna
23. Parry ML, Rosenzweig C, Iglesias A, Livermore V, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob Environ Chang 14:53–67
24. Fischer GM, Shah M, Tubiello FN, Van Velhuizen H (2005) Socio-economic and climate change impact on agriculture: an integrated assessment, 1990–2080. Philos Trans R Soc B 360:2067–2083
25. Schmidhuber J, Tubiello F (2007) Global food security under climate change. Proc Natl Acad Sci 104(50):19703–19708
26. Pegov SA, Khomyakov DM, Khomyakov PM (2000) Vliyanie globalnih izmenenii klimata na socialnoeconomicheskoye polozeniye Rossii (Global change impacts on the socio-economic situation in Russia). In: Kotlyakov VM (ed) Globalniye I regionalnye izmeneniya klimata i ikh

prirodniye i socialnoeconomicheskiye posledstviya (Global and regional climate change and its environmental and socio-economic impacts). Geos, Moscow (in Russian)
27. Mendelsohn R, Morison W, Schlesinger ME, Andronova NG (2000) Country-specific market impact of climate change. Clim Chang 45(3–4):553–569
28. Alcamo J, Dronin N, Endejan M, Golubev G, Kirilenko A (2007) A new assessment of climate change impacts on food production shortfalls and water availability in Russia. Glob Environ Chang 17(3–4):429–444
29. Golubev G, Dronin N (2004) Geography of droughts and food problems in Russia (1900–2000). Report of the International project on global environmental change and its threat to food and water security in Russia. Center for Environmental Systems Research, Kassel
30. Lioubimtseva E, Henebry GM (2009) Potential impact of climate change on the grain productivity in Central Eurasia: human vulnerability and adaptations. In: Nickolova N (ed) Global changes: vulnerability, mitigation, and adaptation. Sofia University St. Kliment Ohridski University Press, Sofia, pp 22–27
31. Lioubimtseva E, Henebry GM (2009) Climate and environmental change in arid Central Asia: impacts, vulnerability, and adaptations. J Arid Environ 73(11):963–977
32. Ioffe G, Nefedova T, de Beurs KM (2012) Land abandonment in Russia: the case of two oblasts. Eurasian Geogr Econ 53(4):527–549. doi:10.2747/1539-7216.53.4.527
33. USDA FAS (2010b) USDA foreign agricultural service. http://www.fas.usda.gov/. Accessed January 2013
34. Friedl MA, Sulla-Menashe D, Tan B et al (2010) MODIS Collection 5 global landcover: algorithm refinements and characterization of new datasets. Remote Sens Environ 114:168–182
35. Morisette JT, Richardson AD, Knapp AK, Fisher JI, Graham E, Abatzoglou J, Wilson BE, Breshears DD, Henebry GM, Hanes JM, Liang L (2008) Unlocking the rhythm of the seasons in the face of global change: challenges and opportunities for phenological research in the 21st Century. Front Ecol Environ 5(7):253–260. doi:10.1890/070217
36. de Beurs KM, Henebry GM (2005) A statistical framework for the analysis of long image time series. Int J Remote Sens 26(8):1551–1573
37. de Beurs KM, Henebry GM (2008) Northern Annular Mode effects on the land surface phenologies of Northern Eurasia. J Climate 21:4257–4279
38. de Beurs KM, Wright CK, Henebry GM (2009) Dual scale trend analysis distinguishes climatic from anthropogenic effects on the vegetated land surface. Environ Res Lett 4:045012
39. de Beurs KM, Ioffe G, Nefedova TG (2012) Agricultural change in the Russian grain belt: a case study of Samara oblast. Geogr Environ Sustain 5(2):95–110
40. OECD-FAO (2011) OECD-FAO agricultural outlook 2008–2017. OECD, Paris, p 230
41. EBRD-FAO (2008) Grain production and export potential in CIS countries. Fighting food inflation through sustainable investment. European Bank for Reconstruction and Development/Food and Agriculture Organization, London
42. Koester U, Striewe L (1998) Huge potential, huge losses – the search for ways out of the dilemma of Ukrainian agriculture. In: Siedenberg A, Hoffmann L (eds) Ukraine at the crossroads: economic reforms in international perspective. Physica, Heidelberg, pp 259–270
43. Serova EV (2000) Russia's agro-food sector: state of the art. In: Wehrheim P, Frohberg K, Serova E, Von Braun J (eds) Russia's agro-food sector: towards truly functioning markets. Kluwer Academic, Dordrecht, pp 81–106
44. Liefert WM, Liefert O, Serova E (2009) Russia's transition to major player in world agricultural markets. Choices 24(2), http://www.choicesmagazine.org/magazine/article.php?article=78. Accessed January 2013
45. Lissitsa A, Odening M (2005) Efficiency and total factor productivity in Ukrainian agriculture in transition. Agric Econ 32(3):311–325
46. Castells M (1999) End of millenium. Blackwell, Malden
47. Leichenko RM, O'Brien KL (2002) The dynamics of rural vulnerability to global change: the case of southern Africa. Mitigation Adap Strat Global Climate Change 7:1–18

48. Almaganbetov N (2005) The impact of land reforms on economic development of Kazakhstan. The Center for Policy Studies, Central European University/Open Society Institute, Budapest
49. Sedik D, Trueblood M, Arnade C (2002) Corporate farm performance in Russia, 1991–95: an efficiency analysis. J Comp Econ 27(3):514–533
50. WHO (2009) World Health Organization Databases. http://www.who.org. Accessed January 2013
51. World Bank (2009) The World Bank Data. http://www.worldbank.org. Accessed January 2013
52. Dudwik N, Fock K (2007) Land reform and farm restructuring in transition countries: the experience of Bulgaria, Moldova, Azerbaijan, and Kazakhstan. World Bank, Washington
53. Sedik D (2004) Missing pillars: the failures of rural finance in Ukraine. In: Macey DAJ, Pyle W, Wegren SK (eds) Building market institutions in post-communist agriculture: land, credit, and assistance. Lexington Books, Lanham
54. Wehrheim P, Wiesmann D (2006) Food security analysis and policies for transition countries. J Agric Dev Econ 3(2):112–143
55. Baydildina A, Akshinbay A, Bayetova M, Mkrytichyan L, Haliepesova A, Ataev D (2000) Agricultural policy reforms and food security in Kazakhstan and Turkmenistan. Food Policy 25(6):733–747
56. IKAR (2010) Institute for Agricultural Market Studies. http://www.ikar.ru/eng/. Accessed January 2010
57. USDA (2009) Global crop production review. USDA's Joint Agricultural Weather Facility. http://www.usda.gov/oce/weather/pubs/. Accessed December 2009
58. Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the extremes: an intercomparison of model-simulated historical and future changes in extreme events. Clim Chang 79:185–211
59. Long SP, Ainsworth EA, Leakey ADB, Nösberger J, Ort DA (2006) Food for thought: lower-than-expected crop yield stimulation with rising CO_2 concentrations. Science 312(5782):1918–1921. doi:10.1126/science.1114722

Part III
Climate Change Mitigation Strategies

Mitigating Climate Change in Urban Environments: Management of Water Supplies

Sarah Lawson

Abstract Energy and water are tightly connected but the possibility of mitigating climate change through water supply decisions has not been fully explored. The potential for improved efficiency is examined through analysis of the water supply systems in the five largest US cities: New York, Los Angeles, Chicago, Houston, and Philadelphia. The energy intensity of water supply in these cities ranges from 0.15 to 1.34 kWh/m^3, largely due to pumping requirements. These cities also demonstrate opportunities to reduce the greenhouse gas emissions from water supply through source water protection, selection of alternative water supplies, repair and replacement of infrastructure, water conservation, and use of alternative energy supplies. Finally, decentralization of water supplies may also provide opportunities for improved energy efficiency in water supply.

Keywords Energy efficiency, Urban water supply, Water treatment, Water utilities

Contents

S. Lawson (✉)
Environmental Studies Program, Randolph College, Lynchburg, VA, USA
e-mail: slawson@randolphcollege.edu

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 145–168, DOI 10.1007/698_2013_224,

1 Introduction

Urban water supply is tied to climate change in multiple ways including the effects of climate change on water supplies and the greenhouse gases produced by water treatment and distribution. Changes in rainfall intensity, extended droughts, decreased snowfall, and a host of other changes will affect the ability of urban water systems to meet water demands. At the same time, these urban water systems will continue to produce greenhouse gases which enhance climate change. Growing population will further stress water supplies and urban water systems will have to adapt to meet these new demands without increasing their contribution to climate change. Because a thorough examination of the relationships between urban water supply and climate change is far beyond the scope of a single chapter, this chapter will focus on opportunities for reducing energy use for urban water supply as a climate change mitigation strategy.

Water supply, treatment, and distribution represent a significant portion of a municipality's energy consumption [1], so modification of urban water supply provides an opportunity for cities to reduce their climate change impacts. To understand the potential for change in urban water supply, the nature of urban water supply must be understood. For simplicity, this chapter will focus on urban water supply in the United States (US), though the lessons learned are applicable in other countries. This examination of urban water supply is particularly important because 80.7% of the US population lives in urban areas, with the population growth in urban areas outpacing overall US population growth [2]. According to the USGS, in 2005, water withdrawals for public supply in the US averaged 167 million m^3 per day with 86% of the US population receiving their water through public water systems (defined as systems that supply 25 or more people or 15 or more connections). Only one-third of this water comes from groundwater sources with the remainder from lakes and other surface waters [3].

The move to regulated public water supplies in the US grew from public health concerns. Epidemics of cholera, typhoid, and other infectious diseases led to the regulation of water supply and pollution through centralized water supply and wastewater treatment systems. According to history provided by the United States Environmental Protection Agency (USEPA), the first city to pump water from a surface source for potable use distribution was Philadelphia in 1799. The prevalence of public water systems steadily increased and by 1900, more than 3,000 public water systems served people in the United States. While these systems distributed water, they generally did not treat it. An understanding of how contaminated water supplies could cause disease began in the mid to late 1800s

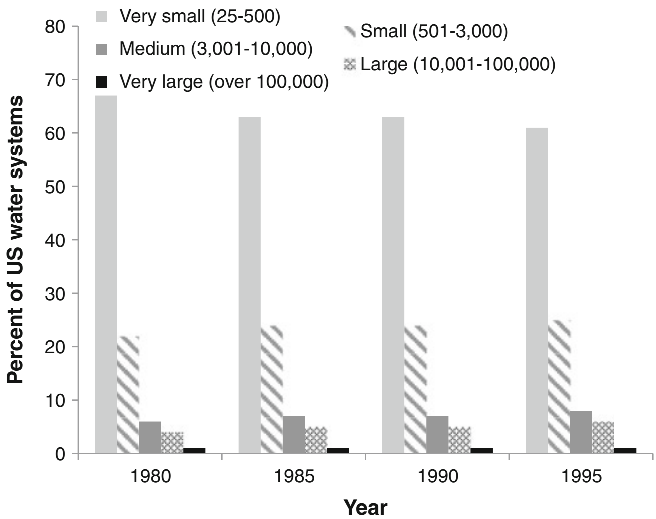

Fig. 1 Percent of US public water systems in five size classes. The percentage of very small systems has declined since 1980 while the percentage of very large systems has remained constant. This change is attributed to the financial benefits of consolidation in the face of increasingly stringent water supply regulations for very small systems (data are from USEPA [4])

when a cholera outbreak was linked to a contaminated well and Pasteur developed the “germ theory” of disease. Jersey City, New Jersey, became the first water system to disinfect its water supply with chlorine in 1908. In 1914, the United States Public Health Service began regulating disease-causing microorganisms in water supplies. These regulations were expanded repeatedly and were eventually adopted with minor changes by all 50 states of US. By the time the Safe Drinking Water Act was passed in 1974, chemical contamination had been added to the list of health concerns in drinking water. The Safe Drinking Water Act was significantly revised in 1986 and 1996. The USEPA, as administrators of the Act, has added additional regulated contaminants and adjusted the guidelines for contaminants in drinking water. Since the 1980s, the percentage of very small water systems, those that serve 25–500 people, has decreased as many of these systems have consolidated (Fig. 1). In addition, more small water systems (serving 500–3,300 people) are providing treatment for the water they supply [4].

These changes in public water supply have dramatically improved the safety and reliability of the US water supply, but additional pumping and treatment have also increased the energy use associated with water supply. Energy is often one of the largest controllable costs of a water utility. However, many of the systems were designed when energy costs were low and energy efficiency was not strongly considered in initial design. In a typical public water system in the US, freshwater is pumped from a surface water or groundwater source to a water treatment plant where the water is filtered and disinfected. The treated water is then pumped through a distribution system of pipes, and potentially additional pumps, to the end use. Each step of this process requires energy, often electricity, and drinking water treatment and distribution and wastewater treatment accounts for 4% of electricity use in the US, with 80% of this electricity used for pumping [1].

Energy use varies widely among water systems with the total volume per day accounting for 76% of the total variation in energy use [5]. Public water systems typically use more energy (0.37 kWh/m^3 for surface water systems and 0.48 kWh/m^3 for groundwater systems) than private wells (0.18 kWh/m^3) [1]. This difference is largely due to the energy required for finished water distribution, which is the largest energy user in urban water supply and distribution [1]. Additional regulations and studies since the original study indicate that energy use for water is increasing [1]. While the EPRI [1] estimate is still widely used, a more recent estimate based on total US energy use for water utilities and the total volume of water supplied by public water systems is an average of 0.51 kWh/m^3 [6]. This is consistent with the mode of 0.36–0.42 kWh/m^3 found in an analysis of data compiled by the American Water Works Association Research Federation [5].

Energy use for water supply is expected to increase as population and requirements for water treatment increase while the quality and quantity of water sources deteriorate. Groundwater is often considered a less energy-intensive source than surface water. However, this balance may shift as the depth to the water table increases. Rothausen and Conway [7] used a simple physical relationship to estimate that pumping 1 m^3 of water 1 m (vertical) uses 0.0027 kWh, assuming the pump runs at 100% efficiency. Based on this calculation, a 1 m drop in the height of the water table will increase the energy intensity of water by 0.0026 kWh/m^3, or 0.26 kWh/m^3 for a 100 m drop in the water table, a value observed in some areas of the US. In addition, much of the energy savings in groundwater use is from decreased need for water treatment. However, the frequency of disinfection of groundwater systems has increased significantly in recent years with 97.6% of community water systems drawing water from groundwater sources using disinfection [8].

Growing public awareness of the inter-relationship between water and energy has increased attention on the energy use for water supply. The US government has recognized the need to improve energy efficiency in water utilities. To help achieve this goal, the USEPA has developed Ensuring a Sustainable Future: An Energy Management Guidebook for Water and Wastewater Utilities as well as an on-line energy use benchmarking tool. The guidebook describes a Plan-Do-Check-Act approach to developing and implementing an energy efficiency plan for a water or wastewater utility. This approach has been used successfully for utilities such as the Santa Clara Valley Water District in California which uses solar energy for 20% of its energy and reduced carbon dioxide emissions by an estimated 187,200 kg/year [4]. Much of the emphasis in these energy efficiency upgrades has focused on wastewater treatment. However, significant energy savings are possible for water supply systems. This chapter is designed to highlight these potential energy savings.

2 Water System Energy Use in Major US Cities

To further characterize the use of energy in urban water supply and the potential to reduce greenhouse gas emissions associated with water supply; this section examines the water utilities in the five most populous cities in the US according to the 2010 census. For each water utility, the source and treatment system are characterized as well as energy use. Peer-reviewed literature on the energy demands of the public water supply is still sparse. This approach is taken to highlight how energy is used in large municipal systems. These descriptions are not full life-cycle analyses and do not include any energy use for the manufacture of materials or facilities. These descriptions are also not complete accounting of the social, political, economic, or environmental status of a water system. The description and assessment are focused solely on energy use and for each utility, and a management practice that decreases the carbon footprint of the utility is selected for further exploration. In general, little attention is given to the source of energy for the water utility, except in cases of alternative energy supplies. Finally an alternative, or supplement, to the entire system of decentralized water treatment and distribution is presented.

2.1 New York City

New York City (NYC) in the State of New York is the most populous US city. NYC is located on a natural harbor in the humid subtropical climate zone. The history of the public water supply in NYC began with a public well in 1677. The modern water supply system was launched in the mid-1800s when the Croton River was dammed and an aqueduct was built to carry water to NYC. A second aqueduct to replace the original Croton Aqueduct was completed in 1893. Today, much of the NYC water supply comes from the Catskills system, which began supplying water to NYC in 1915. In 1937, construction of the Delaware system, which today provides a small portion of the water to NYC, began. As shown in Fig. 2, these three systems can store up to $2{,}195 \times 10^6\ m^3$ of water in upstate New York [9] and supply approximately $3.8 \times 10^6\ m^3$ of water per day to NYC from watersheds up to 232 km away [10].

Despite the distance of travel for water, two features of NYC water supply system make it highly energy efficient. First, because of topography, that is, elevation change, 95% of the water is delivered to customers by gravity, though pumping is used during low water conditions. In addition, in 1993, NYC obtained a Filtration Avoidance Determination from the USEPA for the Catskills and Delaware supplies through continued improvements in watershed protection. The Surface Water Treatment Rule of the National Primary Drinking Water Regulations requires filtration of surface water supplies to reduce contamination from microbial pathogens unless the water system meets a set of avoidance criteria, including

Fig. 2 New York City's water supply system. Water to the city of New York is gravity-fed, predominantly from the Catskills. Because of this use of gravity and the high initial quality of the water, New York City has a highly energy efficient water supply system. Used with permission of the City of New York and the NYC Department of Environmental Quality

source water quality and watershed protection. The lack of conventional filtration is estimated to save NYC 139 million kWh per year [11].

The water from the Catskills/Delaware system is disinfected with chlorine prior to use and a secondary ultraviolet treatment facility is under construction. This ultraviolet treatment facility is necessary to meet USEPA requirements for two types of disinfection on surface water supplies. The New York City Department of Environmental Protection (NYCDEP) is also installing a filtration and treatment system for the Croton system, which is currently offline but typically supplies about 10% of the water to NYC and is not included in the Filtration Avoidance Determination. The Croton filtration system and the ultraviolet light treatment on the Catskills/Delaware system will increase the energy used to supply water to NYC by 5% [11]. The ultraviolet disinfection unit will be installed in the near future with a treatment capacity of 9.1×10^6 m^3 of water per day [12]. Use of this facility will require pressurization of the Catskills Aqueduct through pumping to maintain appropriate pressures and once the filtration and treatment system is completed, the Croton system is expected to supply up to 30% of the water demand [12].

Even with a highly efficient system, NYC water supply still has a greenhouse gas impact. In 2010, water supply to NYC accounted for 0.04 million metric tons of CO_2 equivalent, with 54% of the energy coming from electricity [13]. According to a 2008 study, in the entire New York State, drinking water supply accounts for 0.75–1 billion kWh per year with a statewide average energy use of 0.20 kWh/m^3. The high efficiency of the NYC water supply system significantly affects the statewide averages, where average energy use is 0.23 kWh/m^3 when the Catskill/Delaware and Croton systems are excluded [11]. Based on the total energy use for water supply in 2010 provided in the NYC's greenhouse gas inventory [9] and the estimated water supplied by NYC's water supply system, 4.24×10^6 m^3/day [10], the average energy use per volume for water supply in NYC is 0.18 kWh/m^3. This value is well below the US average for public water systems, but similar to estimates for individual water supplies such as residential wells [1].

2.2 Los Angeles

The City of Los Angeles in the State of California is located in southern California next to the Pacific Ocean and receives little precipitation. The history of water supply in Los Angeles is more recent and involves more controversy. The first water system in Los Angeles began in the late 1700s when some families created a dam to divert water from the Los Angeles River to irrigation ditches. The water system became a city department in 1854 and installed its first water meter in 1889 while leased its operation to a private company. In 1902, the city bought the water system and soon after began looking to the Owens River Valley for an additional water source. Acquisition of the land and rights to the water caused significant conflicts with local residents around Owens River Valley and the federal government, but in 1906, the City of Los Angeles was granted permission to construct an aqueduct to bring water from Owens River Valley. The aqueduct construction was completed in 1913, but city officials were soon looking for more water.

The City of Los Angeles began groundwater pumping, further acquisition of water rights, and attempts to purchase drainage canals, all of which met resistance from the Owens River Valley Irrigation District and local farmers worried about groundwater depletion. The conflict became violent with occasional dynamiting. During this period, the City of Los Angeles also suffered the catastrophic and tragic failure of the St. Francis Dam, which resulted in hundreds of fatalities. In 1928, the Metropolitan Water District of Southern California (MWD) was established to construct the Colorado River Aqueduct, which included construction of what is now known as the Hoover Dam. The 1930s and 1940s saw the reach of the Los Angeles water supply extend 278 km further with the Mono Basin Project and the construction of Crowley Lake Reservoir. Hydroelectric power plants along the Los Angeles Aqueduct were constructed in the 1950s. The final major water supply infrastructure project was the construction of the Second Los Angeles Aqueduct, just south of the now dry Owens Lake bed. This history demonstrates the continued search for water, often far beyond the city's boundaries, to serve population of Los Angeles.

Like New York, much of the water supplied to Los Angeles reaches the city from a long distance by gravity through the Los Angeles Aqueduct, which is a net producer of energy (1.99 kWh/m^3) [14]. However, water supplied by the MWD through the 822-km long California and Colorado Aqueducts is the most energy-intensive water supplied to Los Angeles. As shown in Fig. 3, the California Aqueduct requires six pumping stations and uses 3.12 kWh/m^3 of energy to pass the Tehachapi Mountains [14]. This energy need for water transport by Aqueduct represents 2–3% of California's statewide total energy use [15]. Beyond this lift, the California Aqueduct splits into two branches. Both branches include additional lifts and power generation making the final energy expenditure for transport of water from the California Aqueduct for the two branches 2.09 and 2.62 kWh/m^3 [14].

Once the water reaches Los Angeles, energy is used to treat (average energy use 0.027 kWh/m^3) and distribute the water (average energy use 0.16 kWh/m^3) [14]. The total energy use for water transport from all sources, water treatment, and distribution averages 1.33 kWh/m^3.

The total carbon footprint from water supply in Los Angeles averages 0.43 million metric tons CO_2 per year [14]. The percentage of water supply from the Los Angeles Aqueduct is expected to decrease in coming years requiring increased reliance on more energy-intensive water sources. Currently, recycled water represents only 1% of the water supply. While recycled water is a more energy-intensive water source (1.08 kWh/m^3), it is a less energy-intensive water source than water from the MWD and other sources. Increased use of recycled water presents an opportunity to minimize the increase in energy use for water supplies in Los Angeles.

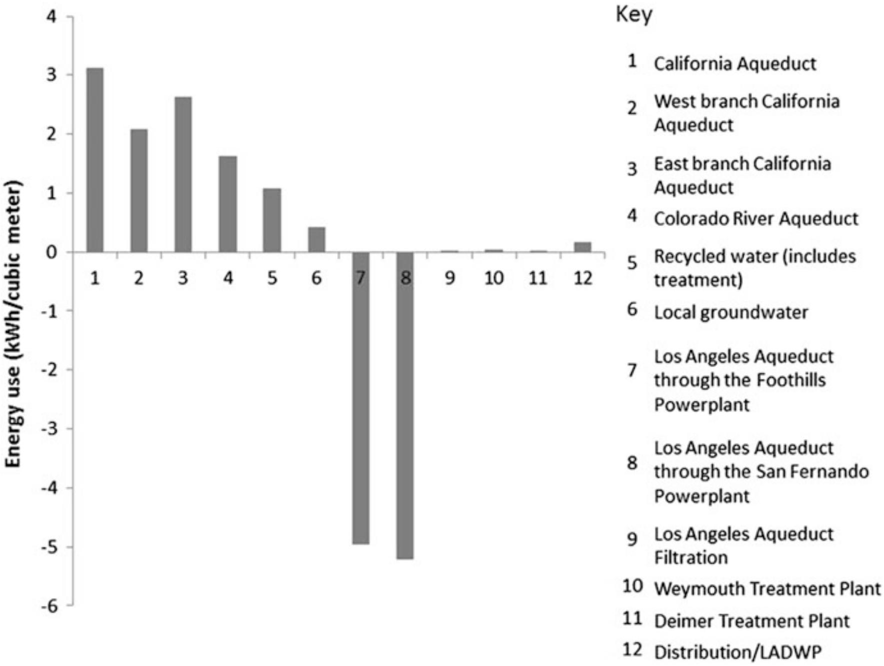

Fig. 3 Energy use for different portions of the City of Los Angeles water supply. Negative values indicate net energy generation. Much of the water supplied to the City of Los Angeles is imported. Because of the terrain, this importation of water can be very energy intensive. This figure shows that treatment and distribution are relatively small portions of the energy use in Los Angeles because of the energy-intensive supply (data from LADWP [14])

2.3 Chicago

The City of Chicago in the State of Illinois is located on the shores of Lake Michigan, one of the Great Lakes, in the humid continental climate zone. Unlike NYC and Los Angeles, the City of Chicago has a local water supply and obtains its water from Lake Michigan for treatment at two water treatment plants. Water flows from these treatment plants to 12 pumping stations throughout the city for distribution. Chicago supplies about three million cubic-meters of water per day to 5.3 million people through 7,778 km of water mains [16]. Until 1900, before the construction of the Chicago Sanitary and Ship Canal, sewage and runoff from the City of Chicago were discharged to the Chicago River which drained to Lake Michigan, significantly impairing Lake Michigan water quality. Furthermore, construction of canals and locks on the Chicago River diverts water from the metropolitan area and away from Lake Michigan. However, this system also diverts stormwater runoff from the Chicago area away from Lake Michigan. The stormwater runoff from 1,743 km^2 now flows to the Mississippi River [17]. While the diversion prevents pollution of Lake Michigan it also decreases the amount of water that enters Lake Michigan and is counted against the State of Illinois's allocation of water from Lake Michigan. Based on a 1967 US Supreme Court decision, the State of Illinois has the right to 90.6 m^3/s of water from Lake Michigan. The diverted runoff accounted for 40.7% of this allowance in 2007, almost as much as the water used for public water supply (47%) [18].

The water from Lake Michigan is treated at two large conventional water treatment plants, the Jardine Water Purification Plant and the South Water Purification Plant, before it travels to 1 of 12 pumping stations for distribution to the City of Chicago. This process uses 0.15 kWh/m^3 of electricity, but because the natural gas used for pumping is not included in this value, the total energy intensity of Chicago's water is underestimated [16]. This electricity use corresponds to 0.11 million metric tons of CO_2 equivalent per year based on values provided in Chicago Greenhouse Gas Emissions: An Inventory, Forecast and Mitigation Analysis [19].

Most of the water distribution system in Chicago is old and nearing the end of its useable life cycle. It is estimated that repairing and replacing this aging infrastructure will save $454 \times 10^3\ m^3$ water per year [20]. The City of Chicago is planning to increase its rate of replacement of water mains to match the rate at which they were installed. In addition, Chicago, like many other cities, faces increasing water treatment challenges as new drinking water contaminants such as pharmaceuticals become regulated. Lake Michigan receives treated wastewater from multiple municipalities and many of these contaminants are not removed in conventional wastewater treatment. Voluntary monitoring of these emerging contaminants by the City of Chicago has found herbicides and pharmaceuticals, such as atenolol, in Lake Michigan and Chicago drinking water [21]. The levels of contaminants found are not considered harmful to human health, but energy-intensive treatment for these contaminants may be required in the future. The issue of emerging contaminants is not unique to Chicago and represents a challenge for many water systems.

2.4 Houston

The City of Houston is the largest city in the State of Texas and is located in the humid subtropical climate zone. According to Smyer [22], in the 1870s, the city contracted with the Houston Water Works Company to provide 10,000 m^3 of water per day from Buffalo Bayou, the main waterway through Houston that was initially used to attract settlers. Frustration over the quality of the delivered water, a lack of sufficient water pressure to fight fires, and the discovery of a large aquifer in 1887 led to increasing reliance on groundwater. However, dissatisfaction with the privately owned water supply company continued and in 1906, the city bought the Houston Water Works Company and created the Water Department which continued groundwater exploration. However, by the 1970s, land subsidence throughout Houston and a state mandate to end it forced City of Houston to decrease reliance on groundwater and increase the use of surface water [22]. In 1991, surface water surpassed groundwater as a water source for Houston [23]. In 2011, groundwater accounted for 14% of the water supply to City of Houston [24].

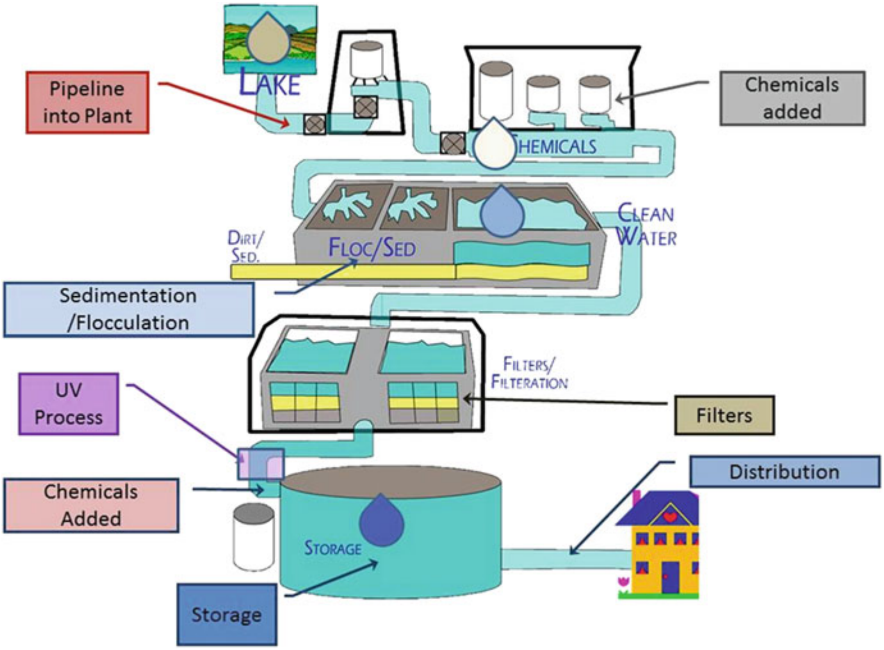

Fig. 4 Houston water treatment process. The water supplied to the City of Houston is treated through multiple processes, typical of a conventional water treatment system. Ultraviolet disinfection is currently not in use in Houston and is only installed at one plant. Used with permission of the City of Houston Waterworks Education Center. Figure created by Jerrel Geisler

At present, the City of Houston receives drinking water from eight water systems. The main system serves approximately 95% of the residents and relies primarily on surface water from Lake Conroe, Lake Houston, and Lake Livingston, while the remaining water systems primarily rely on deep groundwater wells, often deeper than 230 m [24]. The city owns 70% share of Lake Conroe and Lake Livingston, and 100% of Lake Houston but the city does not receive any water from Lake Conroe, obtains only 10% of its water from Lake Houston, making Lake Livingston the primary source of city's drinking water [25]. The three lakes are all managed by independent water agencies. Water supply throughout Texas has been strained by recent severe droughts, which makes effective management of water supply to Houston crucial.

Electricity for the three water treatment plants and pumps stations costs the city an estimated $21.7 million per year [26]. The water treatment plants are conventional treatment systems utilizing a combination of filtration and disinfection (Fig. 4, ultraviolet disinfection is only installed at one plant and is not currently used at any treatment plant). According to the City of Houston's greenhouse gas emissions reduction plan, water production and wastewater treatment combined produce 4.6×10^5 metric tons of CO_2 equivalent per year [27]. Based on an emissions coefficient for ERCOT (Electrical Reliability Council of Texas) [28], this equates to 555 million kWh per year. Using an estimate that 34% of the city's total electricity is used for utilities [29] and assuming that all the fixed sources in the city's greenhouse gas emissions reduction plan [27] represent all the electricity the city purchases, 176 million kWh are attributable to water supply, treatment, and distribution. Based on an average daily supply of 1.4 million m^3 in 2005 (the year for which greenhouse gas emissions were calculated [30]), this electricity use corresponds to 0.33 kWh/m^3. While this estimate requires multiple assumptions, it allows us to put the energy intensity of Houston's water supply into perspective.

2.5 *Philadelphia*

Philadelphia is located in the humid subtropical climate zone and like Chicago, Philadelphia has a local water supply. A yellow fever epidemic in the late 1700s and early 1800s spurred public concern about water supply in Philadelphia and led to development of the "Water Committee" in 1799 [31]. Though later developments showed that yellow fever was not transmitted by contaminated drinking water, the public fear led to the first city water system. The water system quickly felt the strain of energy costs of water distribution and the city built the Fairmount dam and a hydropower system to supply power for water distribution [31]. Public health concerns further pushed changes in the Philadelphia water supply as typhoid deaths created concerns. In 1902, the city began construction of a filtration system and in 1913, the city began disinfecting its water supply, which dramatically decreased typhoid deaths [31]. Philadelphia like Chicago has always used a local and urban water source and has been monitoring the water source for emerging contaminants.

The sources of water supply in Philadelphia are the Schuylkill and Delaware Rivers which converge at Philadelphia. Today, three water intakes, two on the Schuylkill River and one on the Delaware River, supply three water treatment plants. The water treatment plants are conventional plants using settling, disinfection with sodium hypochlorite, coagulation, flocculation, filtration through sand and coal, and final additional chemical addition [32].

From 2003 to 2008, the Philadelphia Water Department spent an average of $18.1 million per year on electricity, using 256 million kWh per year [33]. Based on the volume of water supplied in 2008 (9.7×10^5 m^3/day [32]), the energy use in 2008 equates to 0.77 kWh/m^3. This value includes wastewater treatment energy use. The City of Philadelphia has recognized the need to mitigate greenhouse gas emissions from the water/wastewater sector and is establishing alternative energy projects at some of their wastewater treatment plants. A single biogas cogeneration facility at the Northeast Wastewater Treatment Plant is expected to offset 10% of the Philadelphia Water Department's electricity use and reduce carbon emissions by nearly 20,000 metric tons per year [34].

3 Opportunities for Mitigating Climate Change

The five cities profiled have very different water systems with a wide range of energy use per volume of water produced. All of the cities face common issues of emerging contaminants, growing demand, and strain on supply. All cities also have opportunities to reduce their current energy usage and prevent future increases in energy use. While all of these cities are engaged in a number of conservation initiatives, one key lesson from each city is selected for further exploration. Most of these lessons apply to many if not all of the cities profiled. While the challenges such as topography and available water supply vary from city to city and affect their energy use for water supply, these lessons can be applied to each of the five cities and most urban areas.

3.1 Source Water Protection

Water source protection provides an opportunity for energy conservation. The NYC water system is a good example. The NYC has put forth significant effort to protect the quality of its water source for water supplies. As stated earlier in this chapter, NYC's filtration avoidance determination saves an estimated 139 million kWh per year [11]. In addition, the NYC has taken steps to protect its reservoirs and to preserve natural areas.

The city has protected large areas of land around its water supply watershed, including 34,400 ha from 1996 to 2007 [35]. From 1997 to 2011, the city protected an additional 8,500 ha through land acquisition, making the NYC one of the largest landowners in the watershed [10]. The 83,368 ha of land protected by the NYCDEP can sequester almost 0.9 million metric tons of carbon per year (based on the assumption that the protected area is pine or fir forest and based on the USEPA Greenhouse Gas Equivalencies Calculator [36]). While some of the land included in NYC's source water protection program is likely not forested, this land protection clearly represents a double-benefit in terms of climate change mitigation. In the US, not all drinking water source watersheds are so protected. According to Wickham et al. [37], the typical water supply watershed in the United States is 77% vegetated, but only 3% of this land is protected. Almost a quarter of water supply watersheds in the US lost 1% of their natural vegetation over a period of about 10 years [37].

Public concern and emerging science about pharmaceuticals, personal care products, and other man-made chemicals in the water supply may lead to regulation of these contaminants and require public water system operators to increase water treatment to remove these contaminants.

The importance of source water protection will increase as more contaminants in drinking water are regulated. Increased water treatment almost always corresponds with increased energy use. The 18 National Primary Drinking Water Regulations enforced by the USEPA from 1975 to 2008 represent an annual increased water treatment use of 1.8 billion kWh [38].

In recent years, the USEPA has estimated the additional energy use attributable to implementation of the Disinfectants and Disinfection Byproducts Rule (Stage 2 DBPR) and the Long Term 2 Enhanced Surface Water Treatment Rule LT2ESWTR as 116 million kWh per year [39] and 166 million kWh per year [40], respectively. Because applicable treatment technologies for these two regulations overlap, the total energy use attributable to the regulations will likely be less than the sum of these values, but the on-going implementation of these rules will likely increase greenhouse gas emissions from water supply systems. The Stage 2 DBPR is designed to protect human health by limiting exposure to carcinogenic disinfection byproducts and the LT2ESWTR is intended to improve disinfection to reduce the risk of disease from microorganisms, particularly *Cryptosporidium*. These regulations do not require implementation of any additional treatment if water quality is sufficient. In this way, watershed protection/source water protection will provide significant energy savings if additional treatment is not required.

The energy savings from source water protection will likely increase as additional contaminants are identified and more alternate treatment technologies are implemented. The additional energy use attributable to new regulations stems from the additional energy use needed for advanced water treatment. Disinfection with chlorine is both an inexpensive and low energy use process, with an estimated energy intensity of 0.0026 kWh/m^3 for a typical water treatment plant [1]. However, health concerns and recent regulations are leading many public water systems to either replace their existing disinfection equipment and procedure or add additional treatment, often with increased energy use. Raucher et al. [41] estimated an annual energy use of 0.8 million kWh for a 3.8×10^4 m^3/day water treatment plant with conventional water treatment. When advanced water treatment is added, the energy use increases to 0.9 million kWh with ultraviolet treatment, 2.0 million kWh with 1-log ozone disinfection, and 2.1 million kWh with low-pressure microfiltration/ultrafiltration [41].

Other advanced treatment options could require higher energy demands. In case studies of two water treatment plants, one using microfiltration and the other using reverse osmosis, the life-cycle electricity consumption for water treatment was 0.15 kWh/m^3 and 3.9 kWh/m^3 respectively, highlighting the high energy use of reverse osmosis [42]. The USEPA's Environmental Technology Verification programs tests products designed for alternative water treatment and reports on both their efficacy and their power consumption. The measured values range from 0.014 to 0.084 kWh/m^3 [43–45] for ultraviolet light systems. As shown in Table 1, the energy use of advanced water treatment techniques varies widely, dependent on the type of technology and treatment capacity [46]. These treatment technologies are all more energy intensive than conventional treatment and chlorination, but are often necessary to meet updated water quality standards. The range in energy

Table 1 Energy intensity for selected alternative water treatment technologies[a] [46]

Treatment technology	Energy intensity (kWh/m^3) Min	Max
Chloramines as a secondary disinfectant (ammonia 0.15 mg/L)	7.9×10^{-6}	0.43
Chlorine dioxide	6.1×10^{-5}	0.10
Ultraviolet (40 mJ/cm^2)	7.7×10^{-3}	0.32
Ultraviolet (200 mJ/cm^2)	1.2×10^{-1}	2.60
Ozone (1-log *Cryptosporidium* inactivation)	7.3×10^{-2}	0.17
Microfiltration/ultrafiltration	5.1×10^{-2}	0.15
Granular activated carbon (20 min EBCT, 240 day reactivation frequency)	5.9×10^{-2}	1.26

[a]For granular activated carbon treatment at this scale, natural gas is typically also needed at 5.9×10^{-3} scm/m^3

intensity arises from the range in treatment flow rate, with higher flow rates resulting in lower energy intensity.

In addition, some treatment techniques, such as ozone, directly release greenhouse gases. While treatment technique selection greatly affects gas emission, the impact of initial source water quality cannot be ignored. For example, Twomey et al. [47] estimate that increased nitrate in surface water and groundwater as a result of increased corn production for biofuels could result in use of an additional 2,360 million kWh of energy annually for drinking water treatment to remove nitrate in the affected areas.

3.2 Alternative Water Sources

Using alternative water sources provides an opportunity for energy conservation. The City of Los Angles provides a good example. With a large population in an arid region, the City of Los Angeles obviously faces a particularly difficult water supply situation. While at present water from the Los Angeles Aqueduct supplies the largest portion of drinking water to the City of Los Angeles, the amount and percentage of water supplied from the Los Angeles Aqueduct is expected to decrease in coming years to competing water demands and decreasing snowpack in the Sierra Nevada Mountains. Increase in impervious areas which decrease infiltration has limited the city’s ability to use its groundwater resources, and in some cases require energy-intensive pumping and treatment to remedy the contamination. These factors increase city’s reliance on a most energy-intensive water source, that is, water from the MWD. However, the city is looking to reclaimed and recycled water to meet some of its demands and to reduce its reliance on energy-intensive water from the MWD. In 2009, Los Angeles Department of Water and Power supplied 3.93×10^7 m^3 of recycled water and plans to increase this amount to 7.28×10^7 m^3 or 10% of the current water supply [14]. The city’s goal is to meet all new demand (1.23×10^8 m^3) through a combination of recycled water and a reduction in potable water use of 7.89×10^7 m^3 by 2035 [48]. The effectiveness of water conservation measures was seen in 2009–2010, when mandatory water restrictions resulted in the lowest water use in 15 years [14].

Wastewater reuse is typically less energy intensive than desalination or imported water, partially because of the strict requirements for wastewater treatment before discharge [6]. In a life-cycle assessment of two California water systems, Stokes and Horvath [49] found that desalination was 2–5 times more energy intensive than imported or recycled water, and recycled water was less energy intensive than imported water in southern California. In Los Angeles, recycled water is an energy-intensive water source (1.23 kWh/m^3), but it is significantly less energy intensive than imported water from the California Aqueduct (2.28 or 2.81 kWh/m^3 depending on the route and water treatment plant) (Fig. 3, [14]). As with all water treatment and distribution systems, the energy use varies dependent on the system, but for desalination, water treatment is typically the largest electricity user, largely because of the reverse osmosis systems often used in desalination [49]. Much of the additional energy use for reclaimed or recycled water beyond surface water or groundwater supply is attributable to additional treatment. As requirements for wastewater treatment plants become stricter, the additional energy use for reclaimed or recycled water will likely decrease because the effluent from the wastewater treatment plants will be of higher quality.

Obviously, these efforts are not primarily aimed at greenhouse gas reductions. However, Los Angeles's efforts to increase reliance on local water sources should also decrease the carbon footprint of water supply. The increased use of recycled water should result in financial savings for the city. While recycled water is an energy savings option for Los Angeles only because of the energy intensity of the imported water, other cities should examine the energy intensity of varying water supply options when generating a water supply plan. This consideration is especially important as many cities look to alternative water sources, such as desalination and recycled water, to meet growing water demand.

3.3 Improving Water Infrastructure

Required improvements in water supply infrastructure provide an opportunity for energy conservation. The City of Chicago, for example, is a good case. As in many older cities, aging water infrastructure in the City of Chicago decreases the energy efficiency of Chicago's water system. The most significant issue is water leaks. Water system leaks represent a waste of energy in two ways, the embodied energy of the water and the loss of pressure, and therefore energy, and water loss at the site of the leak. In the US, non-revenue water, water from the supplier that is not billed, is estimated at 2.65×10^7 m^3 [50]. Non-revenue water includes both apparent losses, water that is used but not billed, and real losses, such as leaks. If we consider real losses to be 50% of non-revenue water and use the average energy intensity of

US water supply provided by Arzbaecher et al. [6], these losses represent a daily energy waste of 6.8 million kWh. In Chicago alone, the current increased rate of replacement of the city's water mains will equate to 68,760 kWh of electricity saved per day just from the embodied energy of water (based on the reduction in water loss [20] and the energy intensity of water in Chicago [16]). On average, 240,000 water main breaks occur each year in the US and some old cities, such as Baltimore in Maryland, experience multiple water main breaks per day [51]. According to the USEPA, water utilities will need $200.8 billion (based on January 2007 dollars) in the next 20 years in capital investments in water distribution systems, mostly for replacement and rehabilitation of water mains [52].

Research around the world has shown that the infrastructure replacement can improve overall energy efficiency of a water system. In a case study of replacement of water distribution pipes in Oslo, Norway, Venkatesh [53] found a significant reduction in greenhouse gas emissions from the infrastructure improvement over a 10-year study period. The reduced energy use from water distribution attributable to the replacement of the water pipes was greater than the energy required to manufacture and install new pipe [53]. Similarly, Filion et al. [54] found that a 50-year pipe replacement cycle had the lowest overall energy use (total life cycle of the pipes) because of the increasing friction in older pipes, which required greater operational pumping energy and the energy required to repair leaking pipes. Even without consideration of energy use from water loss due to leaks from older pipes, replacement of pipes before the end of the 75-year estimated useable life had overall energy benefits [54].

Repairing infrastructure can also provide financial benefits for a city. Through an active management program, the Philadelphia Water Department decreased average real water losses from 3.6×10^5 m^3/day (early 1990s) to approximately 2.0×10^5 m^3/day in 2008, for an estimated savings of $3.4 million in treatment and distribution costs [51].

Improvement of pumping infrastructure provides another opportunity for improved energy efficiency. Again, the benefits are twofold: improved pump efficiency and improved pressure management which will reduce leaks. Pumps should be appropriately sized for the demand and run at their most energy efficient point. High efficiency pump and motor systems could save an estimated 2,600–7,800 million kWh annually in the US [6]. Variable frequency drives (VFD's) to control pumps offer a further opportunity for increased energy efficiency. With a VFD, the pump's speed is adjusted to maintain a constant pressure across a wide range of operating conditions, while maintaining high pump efficiency. The estimated potential energy savings from VFD control of pumps in water supply systems are 10–20% of the pumping energy use, for a potential yearly savings of 2,600–5,200 million kWh [6]. The ability of a pump controlled by a VFD to decrease pump speed and avoid increased pressure at lower pumping rates may also help with leak mitigation. These pumping improvements should be combined with overall system optimization to provide the best energy efficiency benefits.

3.4 Water Conservation

Water conservation provides an opportunity for energy conservation. The City of Houston provides a good example. The City of Houston, like many other US cities, has experienced significant droughts in recent years. Houston has enforced mandatory water restrictions and advocated voluntary programs such as the "Green Office Challenge." Property managers and owners receive recognition for achieving a 10% or 30% reduction in water use (in addition to other green goals) and tenants earn points for a score card through green practices and reductions in energy use. The energy benefits of water conservation extend beyond the savings in energy used to supply and treat the water. For example, energy use for heating water is often the most energy-intensive part of the water cycle [55] and accounts for 5% total greenhouse gas emissions in the United Kingdom [56] and may make up 8% of energy use in the US [57]. A life-cycle assessment of the energy use of water concluded that 93–97% of energy use occurred in buildings, primarily as water heating [57]. While this energy use is not a part of the municipal process of supplying water, the potential for increased energy conservation through hot water conservation is significant. An investigation of the potential reduction in greenhouse gases attributable to a 20% reduction in per capita water use in California, emphasizing uses of heated water, indicates that hot water use reduction could reduce greenhouse gas emissions by 3.5 metric tons of CO_2 in 2020 [58]. Water conservation will also reduce the need to search for deeper groundwater sources and alternative water sources such as imported water, desalination and recycled water and reduce the energy needed for wastewater management.

3.5 Alternative Energy Use

Using alternative and renewable energy sources to power water supply systems provides an opportunity to reduce greenhouse gas emissions. In general, the use of alternative energy in the wastewater treatment realm has received more attention because of opportunities for energy generation from biogas. In the US alone, biogas from anaerobic digestion could save 628–4,940 million kWh per year of conventional electricity depending on the degree of implementation [59]. For example, in Philadelphia, a 5.6 MW biogas cogeneration facility at the Northeast Wastewater Treatment plant is expected to reduce greenhouse gas emissions by 171,664 million metric tons of CO_2 equivalent per year [34]. Water treatment plants are also ideal locations for using alternative energy sources such as geothermal, solar, and wind energy. Wind turbines have been installed at wastewater treatment plants in Maine, Ohio, Michigan and solar arrays have been installed in Arizona, California, and New Jersey [60]. While the applicability of these alternative energy practices is dependent on site conditions such as solar energy and wind speed, the often remote locations and large rooftop areas make water and wastewater treatment plants ideal locations for alternative energy projects.

Electricity can also be generated by the movement of water within the water system. For example, the water flow through the Los Angeles Aqueduct system generates about 5.55 kWh/m^3 electricity [14], which can offset some of the carbon emissions from Los Angeles's energy-intensive water supply system. The potential for electricity generation in the water distribution system has also received increased attention. One option in systems which require decreased pressure in part of the distribution system (frequently to reduce leaks) is a pump as turbine (PAT) configuration in which the pump acts as a generator [61]. While a specific pump can only be used as a turbine across a limited range of flow rates and pressures, the commercial availability, availability of spare parts, and low cost of pumps make them an attractive alternative to traditional turbines and may produce quick paybacks [62]. In a case study of a small section of a water system in Italy, a combination of PATs and pressure reducing valves was predicted to produce up to 300 MW of electricity per year while reducing water loss 15.9–28.1% [63].

4 Decentralized Water Systems

Energy savings can be realized by implementing decentralized water supply systems. Decentralized water systems are local, relatively small systems that supply potable or non-potable water close to the end use and treat and reuse stormwater runoff and wastewater at the local level [64]. The dominant energy use in most public water systems is pumping of finished water, which will inherently depend on the topography and the distance water is pumped. Decentralized water systems reduce this pumping requirement and can therefore reduce the energy consumption. Decentralized systems also reduce the total demand for piping and may reduce water loss due to leaks because of this reduced pipe distance.

Rainwater harvesting systems are a specific type of decentralized system which may provide even greater energy savings. Rainwater harvesting systems collect and store precipitation runoff from the roof surface for later use. While water distributed through conventional centralized water systems is treated to potable levels, captured rainwater can be used for non-potable uses and replace energy-intensive potable water. Unlike recycled water systems, which require extensive infrastructure, distribution pumping, and treatment, rainwater harvesting systems can be highly energy efficient. Energy use estimations vary widely for rainwater harvesting systems. In an empirical estimate and a measured case study of energy use for a commercial rainwater harvesting system, Ward et al. [65] found that the rainwater harvesting system was more energy efficient than using water from the public water supply. Results in the literature vary widely with some papers showing dramatic decreases in energy use as a result of rainwater harvesting and others showing increased energy use with rainwater harvesting [64, 66, 67]. A thorough analysis of the differences between these studies is beyond the scope of this chapter.

Table 2 Total statewide energy use for water utilities (wastewater is not included)

State	kWh/m^3	Yearly average (million kWh)	Yearly average (millions of $)	Sources
Massachusetts	0.40	386	50	[59]
Illinois	–	388	30	[16]
Wisconsin	0.42	345	18	[68]
New York	0.20	750–1,000	–	[11]
California	–	14,000	–	[15]
US total	–	75,000	–	[59]

However, important factors to consider when comparing these studies include appropriateness of design of the rainwater harvesting system and fair comparison of systems in terms of their carbon footprint. The additional benefit of rainwater harvesting from an energy perspective is a reduction in stormwater runoff. In cities with combined sewer systems or other systems that treat stormwater discharges, energy use will be further reduced by a rainwater harvesting system because it will decrease the volume of runoff.

5 Conclusions

Across the US, large quantities of energy, primarily electricity, are used to supply water through public water systems (Table 2). Improving the efficiency of these systems can help mitigate climate change through less energy use and reduction in greenhouse gases. Efficiency is particularly important given the many challenges facing water utilities such as increasing demand, emerging contaminants, and the effects of climate change on water resources.

The ties between energy and water are complex and have not been fully explored, particularly in reference to the use of energy to supply water. All urban water systems must utilize a variety of strategies and all water users must work to improve water use efficiency, particularly as population increases. There is a need for careful planning and a multifaceted approach to respond to continued strains of the public water supply while mitigating climate change. Frameworks for evaluating the climate change impact of urban water supply have been and are being developed [69–71]. These frameworks can help guide designers and policy makers as they attempt to mitigate climate change while managing water resources affected by climate change.

References

1. EPRI (2002) Water and sustainability: U.S. electricity consumption for water supply and treatment – the next half century. EPRI, Palo Alto

2. US Census Bureau (2010) 2010 Census urban and rural classification and urban area criteria. http://www.census.gov/geo/www/ua/2010urbanruralclass.html. Accessed 21 August 2012
3. Kenny JF, Barber NL, Hutson SS, Linsey KS, Lovelace JK, Maupin MA (2009) Estimated use of water in the United States in 2005. U.S. Geological Survey Circular 1344, Reston, 52 p
4. USEPA (1999) 25 years of the safe drinking water act: history and trends. USEPA, Washington
5. Carlson SW, Walburger A (2007) Energy index development for benchmarking water and wastewater utilities. Awwa Research Foundation, Denver
6. Arzbaecher C, Carns K et al (2009) Program on technology innovation: electric efficiency through water supply technologies – a roadmap. Electrical Power Research Institute, Palo Alto
7. Rothausen SGSA, Conway D (2011) Greenhouse-gas emissions from energy use in the water sector. Nat Clim Chang 1:210–219. doi:10.1038/NCLIMATE1147
8. McCray K (2003) Ground water's role in U.S. community water systems: how the EPA measures it. Water Well J 57(8):38–41
9. New York City (NYC) (2012) History of New York City's water supply system. http://www.nyc.gov/html/dep/html/drinking_water/history.shtml. Accessed 30 August 2012
10. New York City Department of Environmental Protection (NYCDEP) (2011a) New York City 2011 drinking water supply and quality report. http://www.nyc.gov/html/dep/pdf/wsstate11.pdf. Accessed 6 July 2012
11. Pirne M, Yonkin M (2008) Statewide assessment of energy use by the municipal water and wastewater sector. New York State Energy Research and Development Authority, Albany
12. New York City Department of Environmental Protection (NYCDEP) (2011b) Strategy 2011–2014. http://www.nyc.gov/html/dep/pdf/strategic_plan/dep_strategy_2011.pdf. Accessed 6 July 2012
13. Dickinson J, Tenorio A (2011) Inventory of New York City greenhouse gas emissions. http://www.nyc.gov/html/om/pdf/ccp_report041007.pdf. Accessed 8 August 2012
14. LADWP (2010) Urban water management plan. https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-water/a-w-sourcesofsupply;jsessionid=Z91sQSjQ2PVMy20hJVXQjSdNrn5SvtJVymXqSmvM4QTsJnhc8MKr!6863530?_adf.ctrl-state=jutxez8u2_21&_afrLoop=238767582833675&_afrWindowMode=0&_afrWindowId=null#%40%3F_afrWindowId%3Dnull%26_afrLoop%3D238767582833675%26_afrWindowMode%3D0%26_adf.ctrl-state%3D1dlyo1qa7b_4. Accessed 8 August 2012
15. Cohen R, Nelson B, Wolff G (2004) Energy down the drain: the hidden costs of California's water supply. Natural Resources Defense Council, New York
16. Illinois Society American Water Works Association (ISAWWA) (2012) Water energy nexus survey summary report. http://c.ymcdn.com/sites/www.isawwa.org/resource/collection/82A33FB3-E26F-4EA1-932D-866A9E8E264A/FY12-0077_ISAWWA_SURVEY_REPORT_REV_lowres.pdf. Accessed 1 August 2012
17. Metropolitan Planning Council (MPC) (2009) Before the wells run dry: ensuring sustainable water supplies for Illinois. http://www.metroplanning.org/uploads/cms/documents/before_the_wells_run_dry.pdf. Accessed 30 July 2012
18. US Army Corps of Engineers (USACE) (2007) Lake Michigan diversion accounting: water year 2007 report. Chicago
19. Center for Neighborhood Technology (CNT) (2008) Chicago greenhouse gas emissions: an inventory, forecast and mitigation analysis. http://www.cnt.org/repository/Chicago-Climate-Analysis-Final.pdf. Accessed 8 August 2012
20. City of Chicago (2003) Chicago's water agenda 2003 http://www.cityofchicago.org/dam/city/depts/water/general/CmsrOffice/wtrAgenda/wateragenda_1.pdf. Accessed 1 September 2012
21. City of Chicago (2011) City of Chicago emerging contaminants study: analysis of endocrine disrupting chemicals, pharmaceuticals and personal care products. http://www.cityofchicago.org/content/dam/city/depts/water/WaterQltyResultsNRpts/analities/Rnd6tbl20110119.pdf. Accessed 8 August 2012

22. Smyer S (2008) History of the City of Houston's drinking water operations. http://documents.publicworks.houstontx.gov/documents/divisions/utilities/history_of_drinking_water_operations.pdf. Accessed 24 August 2012
23. City of Houston (2010a) Electricity reliability service for water utility: budget and fiscal affairs committee briefing. http://www.houstontx.gov/council/1/bfacommittee/10.5.10/sb361presentation.pdf. Accessed 6 August 2012
24. City of Houston (2011) Drinking water quality report. http://documents.publicworks.houstontx.gov/documents/divisions/utilities/water_quality_report_2011.pdf. Accessed 10 August 2012
25. City of Houston (2012) Drinking water operations. http://www.publicworks.houstontx.gov/utilities/drinkingwater.html. Accessed 15 August 2012
26. City of Houston (2010b) City of Houston surface water conversion. http://documents.publicworks.houstontx.gov/documents/divisions/utilities/coh_surface_water_conversion.pdf. Accessed 30 July 2012
27. City of Houston (2008) Green Houston emissions reduction plan. http://www.greenhoustontx.gov/reports/emissionreduction20080909.pdf. Accessed 5 August 2012
28. Deru M, Torcellini P (2007) Source energy and emission factors for energy use in buildings. National renewable energy library. Technical report NREL/TP-550-38617, Golden
29. City of Houston (2010c) Press release: City of Houston launched wastewater treatment plant energy efficiency project. http://www.houstontx.gov/mayor/press/20100125.html. Accessed 20 August 2012
30. City of Houston (2005) Drinking water quality report. http://documents.publicworks.houstontx.gov/documents/divisions/utilities/water_quality_report_2011.pdf. Accessed 5 August 2012
31. Kramek N, Loh L (2007) The history of Philadelphia's water supply and sanitation system: lessons in sustainability for developing urban water systems. Philadelphia Global Water Initiative, Philadelphia
32. Philadelphia Water Department (2008) Annual drinking water quality report. http://www.phila.gov/water/pdfs/WQR2008.pdf. Accessed 25 August 2012
33. City of Philadelphia (2009a) Alternative energy. http://www.phila.gov/green/greenworks/energy_Alternative.html. Accessed 18 August 2012
34. City of Philadelphia (2009b) Greenworks Philadelphia. http://www.phila.gov/green/greenworks/2009-greenworks-report.html. Accessed 19 August 2012
35. USEPA (2010) New York: New York City and seven Upstate New York counties – effective watershed management earns filtration waiver for New York. USEPA, Washington. http://water.epa.gov/infrastructure/drinkingwater/sourcewater/protection/casestudies/upload/Source-Water-Case-Study-NY-NY-City-7-Upstate-Counties.pdf. Accessed 24 August 2012
36. USEPA (2011b) Greenhouse gas equivalencies calculator. USEPA, Washington. http://www.epa.gov/cleanenergy/energy-resources/calculator.html. Accessed 24 August 2012
37. Wickham JD, Wade TG, Riitters KH (2011) An environmental assessment of United States drinking water watersheds. Landsc Ecol 26(5):605–616. doi:10.1007/s10980-011-9591-5
38. Reiling SJ, Roberson JA, Cromwell JE III (2009) Drinking water regulations: estimated cumulative energy use and costs. J Am Water Works Assoc 101(3):42–53
39. USEPA (2005a) Economic analysis for the final long term 2 enhanced surface water treatment rule. USEPA, Washington, EPA 815-R-06-001
40. USEPA (2005b) Economic analysis for the final Stage 2 Disinfectants and Disinfection Byproducts rule. USEPA, Washington, EPA 815-R-05-010
41. Raucher RS, Cromwell JE III, Cooney K et al (2008) Risk and benefits of energy management for drinking water utilities. AwwaRF, Denver
42. Vince F, Aoustin E, Breant P, Marechal F (2008) LCA tool for the environmental evaluation of potable water production. Desalination 220:37–56
43. NSF (1999) Environmental technology verification program verification statement: Calgon carbon corporation oxidation technologies, Sentinel™ Ultraviolet Reactor (R-11, Model 6-1). NSF International, Ann Arbor

44. NSF (2002a) Environmental technology verification reports: inactivation of MS2 virus in drinking water. Trojan Technologies Inc. UVSwift Ultraviolet System Model 4L12. NSF International, Ann Arbor
45. NSF (2002b) ETV joint verification statement: inactivation of MS2 virus in drinking water. Atlantic Ultraviolet Corporation. Megatron Unit Model M250. NSF International, Ann Arbor
46. USEPA (2005c) Technologies and costs document for the final Long Term 2 enhanced surface water treatment rule and final Stage 2 Disinfectants and Disinfection Byproducts rule. USEPA, Washington, EPA 815-R-05-013
47. Twomey KM, Stillwell AS, Webber ME (2010) The unintended energy impacts of increased nitrate contamination from biofuels production. J Environ Monit 12:218–224
48. LADWP (2008) Securing LA's water supply: City of Los Angeles water supply action plan. http://www.lacity.org/mayor/stellent/groups/electedofficials/@myr_ch_contributor/documents/contributor_web_content/lacity_004714.pdf. Accessed 8 August 2012
49. Stokes J, Horvath A (2005) Life cycle energy assessment of alternative water supply systems. Int J Life Cycle Assess 11(5):335–343
50. Environmental Financial Advisory Board (EFAB) (2010) Water loss reduction financing mechanisms for drinking water distribution systems. United States Environmental Protection Agency, Washington
51. USEPA (2011a) Aging water infrastructure research: science and engineering for a sustainable future. USEPA, Washington, EPA 600-F-11-010
52. USEPA (2009) Drinking water infrastructure needs survey and assessment: fourth report to congress. Office of Water, USEPA, Washington, EPA 816-R-09-001
53. Venkatesh G (2012) Cost-benefit analysis – leakage reduction by rehabilitating old water pipelines: case study of Oslo (Norway). Urban Water J 9(4):277–286. doi:10.1080/1573062X.2012.660960
54. Filion YR, MacLean HL, Karney BW (2004) Life-cycle energy analysis of a water distribution system. J Infrastruct Syst 10:120–130. doi:10.1061/(ASCE)1076-0342(2004)10:3(120)
55. Griffiths-Sattenspiel B, Wilson W (2009) The carbon footprint of water. River Network, Portland. http://www.rivernetwork.org/sites/default/files/The%20Carbon%20Footprint%20of%20Water-River%20Network-2009.pdf
56. Department for Environment Food and Rural Affairs (DEFRA) (2008) Future water: the government's water strategy for England. The Stationary Office, Norwich
57. Arpke A, Hutzler N (2006) Domestic water use in the United States: a life-cycle approach. J Ind Ecol 10(1–2):169–184
58. Haley B, Gallo J-B, Kehr A, Perry M, Siao D, Smallen W, Torn MS, Williams JH (2012) The 2020 emissions reduction impact of urban water conservation in California. J Water Clim Chang 3(2):151–162. doi:10.2166/wcc.2012.047
59. Stillwell AS, Hoppock DC, Webber ME (2010) Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus. Sustainability 2 (4):945–962. doi:10.3390/su2040945
60. USEPA (2008) Ensuring a sustainable future: an energy management guidebook for wastewater and water utilities. USEPA, Washington, EPA 832-R-08-002
61. Ramos H, Borga A (1999) Technical note: pumps as turbines: an unconventional solution to energy production. Urban Water 1(3):261–263
62. Giugni M, Fontana N, Portolano D (2009) Energy saving policy in water distribution networks. In: International conference on renewable energies and power quality, European Association for the Development of Renewable Energies, Environment and Power Quality, Valencia, 15–17 April 2009
63. Fontana N, Giugni M, Portolano D (2012) Loss reduction and energy production in water-distribution networks. J Water Resour Plann Manage 138:237–244. doi:10.1061/(ASCE)WR.1943-5452.0000179
64. Younos T (2011) Paradigm shift: holistic approach for water management in urban environments. Front Earth Sci 5(4):421–427

65. Ward S, Butler D, Memon FA (2012) Benchmarking energy consumption and CO_2 emissions from rainwater-harvesting systems: an improved method by proxy. Water Environ J 26 (2):184–190
66. Grady C, Younos T (2008) Analysis of water and energy conservation of rainwater capture system on a single family home. Virginia Water Resources Research Center, Blacksburg, SR39-2008
67. Parkes C, Kershaw H, Hart J et al (2010) Energy and carbon implications of rainwater harvesting and greywater recycling. Environment Agency, Almondsbury, SC090018
68. Elliot T, Zeier B, Xagoraraki I, Harrington GW (2003) Energy use at Wisconsin's drinking water facilities. Report 222-1. Energy Center of Wisconsin, Madison
69. Janse T, Wiers P (2007) The climate footprint: a practical tool to address climate change. Water Sci Technol 56(4):157–163. doi:10.2166/wst.2007.547
70. van der Hoek JP (2012) Towards a climate neutral water cycle. J Water Clim Chang 3 (3):163–170. doi:10.2166/wcc.2012.015
71. Chang N, Qi C, Yang YJ (2012) Optimal expansion of a drinking water infrastructure system with respect to carbon footprint, cost-effectiveness and water demand. J Environ Manage 110:194–206. doi:10.1016/j.jenvman.2012.06.004

The Impact of Urban Water Use on Energy Consumption and Climate Change: A Case Study of Household Water Use in Beijing

Yuan-sheng Chen, Lu Li, Lei Jiang, Caitlin Grady, and Xin-hui Li

Abstract Water use and energy consumption are intrinsically linked. Understanding the energy consumption linkages in urban water end use is useful in the integrated management of water and energy, amplifying the potential for energy saving by water conservation and thus reducing greenhouse gas emissions of cities. This reduction in energy and emissions in combination with other efforts can contribute to mitigating climate change. This chapter studies the conditions of energy consumption in household water use in urban Beijing by combining two methods: energy use measurements and random sampling social behavior survey. This research analyzes the characteristics of household water end use and estimates the energy intensity of household water use in summer and winter in Beijing. The main conclusions of this study are as follows: about 70% of the energy consumed in household water use lies in bathing, and the energy use related to washing varies remarkably in summer and winter; on average, the energy intensity of household water use in Beijing is 5.94 kWh/m^3 in summer and 9.78 kWh/m^3 in winter; in 2010, the total amount of energy use of household water use in Beijing is about 4.88×10^9 kWh, which accounts for 0.9% of Beijing's total energy consumption. The conclusions show a great potential for energy conservation in household water saving.

Y.-s. Chen (✉) and L. Jiang
Institute of Geographical Sciences and Natural Resources Research, CAS, Beijing 100101, China
e-mail: chenyuansheng@igsnrr.ac.cn

L. Li
Institute of Geographical Sciences and Natural Resources Research, CAS, Beijing 100101, China

China Science and Technology Museum, Beijing 100012, China

C. Grady
Ecological Sciences Engineering Program, Purdue and University, West Lafayette, IN 47907, USA

X.-h. Li
Beijing's 13th Middle School, Beijing 100009, China

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 169–198, DOI 10.1007/698_2013_222,

Keywords Beijing, Energy consumption, Household water use, Water resources

Contents

1 Introduction

In modern cities the water cycle from source to tap involves multiple energy intensive steps. Water resources are often extracted from outside the city and transported through piped systems to water supply plants, purified and treated, then pumped to millions of end users in various corners of cities. Wastewater is then recollected through piped systems from the end user to wastewater treatment plants, treated up to the standards, then discharged to natural water bodies, or used as recycled water. All of these steps in the process constitute an artificial water system of water resources exploitation and utilization in modern cities, known as the exploitation and utilization chains of urban water resources. The chain is divided into five links: water intake and transportation from water source areas, water supply treatment, water distribution, water end use, and wastewater collection and treatment [1, 2]. Each link requires huge amounts of energy. Among them, four links including water intake and transportation from water source areas, water supply treatment, water distribution, and wastewater recollection and treatment are generally called as water supply and discharge industry, known to all as energy consuming intensive industry. However energy consumption in the fourth link of water end use is often ignored by the literature. Energy consumption of water end use is the energy cost within water end users, such as households, factories, hotels, etc. It is related to water appliances, water-use behaviors of water users, weather conditions, and other factors. Previous studies have shown that there is huge energy consumption in the water end use link but have yet to offer suggestions for potential energy-saving opportunities [1, 3]. Studies carried out by Ronnie Cohen and

Gary Wolff for the US Natural Resources Protection Committee and Pacific Ocean Institute indicate "energy intensity of urban water end use accounts for more than 50% of total energy intensity of water system" [1]. Cohen and Wolff [1] also indicate that there is great potential for energy savings in reducing water use of end users, since less water consumed less water needs to be exploited, treated, and pumped before and after use. In order to improve this area, it is important to study energy consumption behaviors of water end users in order to make people aware of huge energy consumption in daily water use. Simultaneously reducing domestic energy use and wastewater discharge can contribute to the reduction of human impacts on the earth. This paper focuses on case study of household water use in Beijing, to explore energy consuming characteristics in water end use, as well as impacts on urban total energy consumption.

2 Background Information

2.1 General Conditions of Water Resources in Beijing

Beijing is located in north side of North China plain, between east longitude 115°20′ and 117°30′, north latitude 39°28′ and 41°05′, with an area of 16,410 km^2. In the west, north, and north-east parts, there are mountainous areas, accounting for 61% of the total area, plain in south-east part, accounting for 39% of the total area.

Beijing's average annual precipitation between the years 1956 and 2000 was 585 mm. This precipitation yields approximately 1,727 million cubic meters (MCM) of surface water resources and 2,559 MCM of groundwater resources. The total amount of local self-produced water resources available is 3,739 MCM [4]. Precipitation is influenced by vapor stream supply conditions, geographical location, and geomorphology, distributed unevenly in both time and space. Rainy periods and dry periods alternate throughout the year. Precipitation in the rainy season (June–September) accounts for 85% of the total year precipitation. Floods during the rainy season often cause major infrastructure and resource problems while in the dry season little precipitation and high demands for water cause Beijing to experience water stress and shortages.

According to the population of 19.61 million in 2010, the annual water resources per capita in Beijing is 118m^3, far below international water shortage limit of 1,000 cubic meters per capita. With an increasing population, Beijing has and will continue to have serious water stress. In China as a whole, the per capita water resources are 2,300 m^3 or about 20 times more than that of Beijing city.

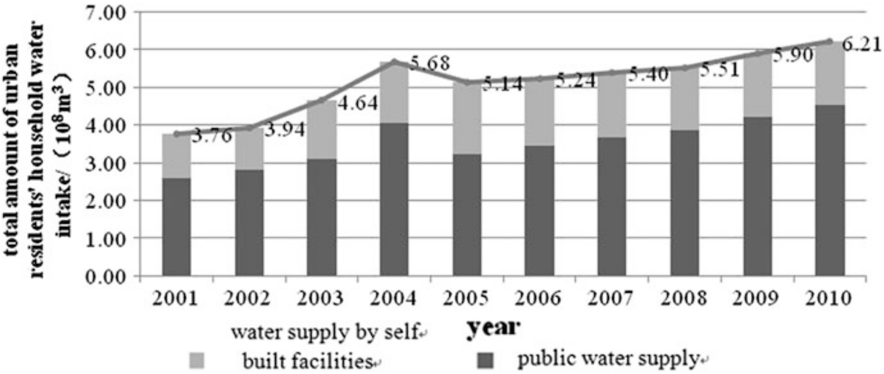

Fig. 1 Urban residents' household water intake amount in Beijing municipality and water supply structure [5]

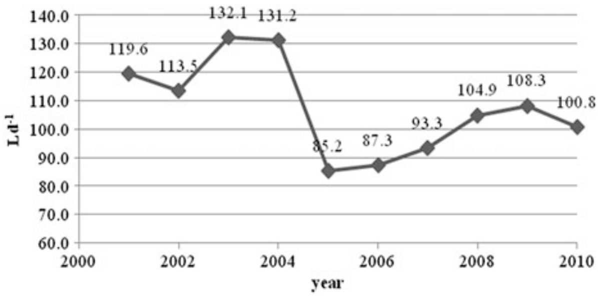

Fig. 2 Urban residents' daily water use per capita in Beijing municipality [5]. Note: per capita per day water use = (public water supply + self-constructed water supply/public water supply population + self-constructed water supply population)

2.2 Daily Urban Resident Water Use in Beijing Municipality

Along with economical and social development, in Beijing municipality, urbanization ratio is over 80%. With constant population growth, living standards have increased, leading to an increase in daily water use of urban residents. Figure 1 shows variation of urban residents' daily water use in Beijing municipality during the period of 2001–2010. During that time the amount of urban residents' daily water intake increased by 65.2%, from 376 MCM to 621 MCM. In the year 2010, urban residents' daily water-use amount accounts for 17.6% of the total city water intake amount of Beijing (3,520 MCM).

Figure 2 shows per capita level of urban residents' daily water use in Beijing municipality. It is seen that per capita level of urban residents' water use during the period of 4 years from 2001 to 2004 is obviously higher than per capita level after 2005. The probable reason is that urban water saving measures have been further strengthened since 2005. In the period of 2005–2009, per capita daily water use of urban residents shows slow growth trend, from 85.2 L per capita per day to 108.3 L per capita per day, with annual growth rate of approximately 5%. In 2010, Beijing urban residents' daily water use per capita has reduced from 108.3 L per capita per day in 2009 to 100.8 L per capita per day in 2010, with the rate of 6.9%. The positive effects could be due to the education and outreach programs developed by the Beijing municipality in order to advertise nontraditional water resources utilization and water-saving measurements.

3 Methods

This study focuses on energy consumption within households in urban residents due to daily water use. Energy consumption in water supply plants, water supply distribution pipe network, wastewater pipe network, and wastewater treatment plants is not taken into consideration.

The energy intensity of households daily water use represents energy consumed in unit water consumed, the unit is generally as kwh/m^3, and calculation formula is expressed as formula (1):

$$e_u = \frac{\sum_{i=1}^{n} E_{ui}}{Q}. \tag{1}$$

In this formula, e_u is the energy intensity, unit generally as kJ/m^3 or kwh/m^3; E_{ui} is the energy consuming amount in a specific period for water end use i, unit as kJ or kwh; Q is the total amount of household water use, unit as m^3; i is the water end use type; n is the total number of types in water end use.

In Beijing, there are seven types of household daily water use including bathing, sanitation demands, washing clothes, kitchen water use, water use for face washing and teeth brushing, drinking water use, and water use for household cleaning. The most complex within this category is water use in kitchens. Due to the complexities associated with water use for everything from washing vegetables to running a dishwasher, the water use was not a target for this research. Toilet water use was also not involved. This study only focuses on four other types of household water use. The energy intensity of household water use was analyzed through theoretical calculation using the amount of water used and water temperature.

In Beijing, each household has one independent water gauge meter but further detailed meter data were unavailable. Residents are not aware of the amount and temperature of their daily water use in different types. Therefore, according to the needs of research, an actual measurement test was designed to obtain important parameters revealing characteristics of end use of water in urban residents. Meanwhile, a sampling survey was designed and carried out to collect more detailed

Table 1 Basic conditions of case study families

	Family members		Residence area (m^2)	Family monthly income ($)	Highest education level of family members
	Members	Family component			
Family 1	3	Middle-aged parents, daughter (senior high school)	45	1,119–1,599	University
Family 2	4	Grandpa, grandma, aunt, baby	104	7,000–10,000	University
Family 3	3	Middle-aged parents, son (senior high school)	105	16,000	University
Family 4	3	Middle-aged parents, daughter (senior high school)	60	7,000–10,000	University

information about actions related to urban household water use and provide data to implement statistical inference of energy intensity of household water use in urban areas of Beijing.

3.1 Household Water-Use Data Collection

This test was designed to gain basic parameter values for calculating energy intensity of household water use, specially the amount of single water use and water temperature of different water end use types, which are unobtainable by other means in China. (The parameter values acquired from this test are shown in Table 12.)

In water-use test, study team selected four typical urban households in Beijing; each family was required to record every water-use behavior of all family members every day during the test on "daily water use records" (see Appendix 1), as well as a family background form and a form about water end use facilities, respectively, documented in Appendixes 2 and 3.

Basic conditions of households' residences and population component of case study families are shown in Table 1. It is necessary to point out that constrained by time, manpower resources and funds, it was not possible to complete tests that replicated the complex differences in Beijing household characteristics. We believe that the four households selected provide an introductory sample of the types of water use found in Beijing.

Of the four families, one family carried out long-term non-interrupted observation for 69 days. The other three households had 1-week observation in summer and 1-week observation in winter separately. The specific test periods are shown in Table 2. It should be noted that the inconsistence of the test periods of four families is caused by the different available time for the test of these families. As this test

Table 2 Data acquisition in case study families

Effective specimen	Effective recording period1 – summer	Recording days	Effective recording period2 – winter	Recording days
Family 1	From July 30, 2011 to September 16, 2011	49	From November 1 to December 31, 2011	61
Family 2	From July 24 to 29, 2011	6	From December 20 to 26, 2011	7
Family 3	From August 15 to 21, 2011	7	From January 15 to 21, 2012	7
Family 4	From August 15 to 21, 2011	7	From January 15 to 21, 2012	7

needs the family members to measure and record their own water-use data, full cooperation of the family members is essential for the test and thus the test periods depend on the available time of the participant families. The difference in test periods may have some effect on the results; however, limited by the research conditions, this question remains to further study.

Water end use facilities in four families are basically same, including heater, bath shower, washing machine, and toilet flushing. All heaters are gas heaters. Family 2 use drum washing machine, other three families use automatic pulsate washing machines. Compared with pulsate washing machine, drum washing machine can save water but cost more electricity. So family 2 is different from other three families, in washing machine water use and energy consumed. In bath shower, all flow rate from family 1 to 4 are tested and are as follows: 0.05–0.09, 0.128, 0.2, 0.125 L/s. Related parameters of heaters, washing machines, and bath showers in four case families are shown in Table 3.

3.2 Random Sampling Survey of Household Water Use in Beijing

This study adopted a random sampling method to collect data for statistical inference of energy intensity of household water use in urban areas of Beijing. The total number of sampling surveys was 246 which yielded an initial response rate of 96.7%. Unfortunately, 42 questionnaires were screened out as outliers and were not used because of self-contradictory and irrational responses. As a result, 195 copies of questionnaires were effective.

A self-designed questionnaire was used in the sampling survey. The questionnaire included three parts. The first part was aimed to acquire general information of sampled families. General information collected included the family size, age, education level, average monthly income, residential area, etc. The highest education level of family members was categorized into four subgroups: below senior high school/polytechnical school, college, university, and master & above. The average monthly income was divided into five subgroups: below ¥4,000 (about $619[1]), ¥4,000–7,000 ($619–1,084), ¥7,000–10,000 ($1,084–1,548), ¥10,000–16,000 ($1,548–2,477), and

Table 3 Parameters of major water-use facilities in four case families

		Washing machine					Bath shower
	Heater type	Type of washing machine	Brand	Energy efficiency class[a]	Water consumption (L/each working cycle)	Power consumption (kWh/each working cycle)	Flow rate (L/s)
Family 1	Gas	Automatic pulsate	Hi-sense XQB50-C8227	2	119	0.085	0.05–0.09
Family 2	Gas	Drum washing	Simens WS10M460T1	1	65	1.05	0.128
Family 3	Gas	Automatic pulsate	LG XQB50-97SF	3	140	0.147	0.2
Family 4	Gas	Drum washing	Sanmsung WF-R865	–	83.2[b]	1.4[b]	0.12–0.125

[a]"Energy efficiency class" is set by General Administration of Quality supervision, Inspection and Quarantine of the People's Republic of China in the national standard of "the maximum allowable values of the energy consumption and Energy efficiency grade for household electric washing machines" (No. GB 12021.4-2004)

[b]In family 4, energy consumption and water consumption of the washing machine are not available; calculation is based on state standard on class of energy consuming limitation and energy efficiency of electrical washing machine, upper limit of class 3

above ¥16,000 ($2,477). Households' residential area was classified into six categories: class 1 represents households' residential area smaller than 50 m^2, class 2 represents equal or larger than 50 m^2 but smaller than 70 m^2, class 3 represents equal or larger than 70 m^2 but smaller than 90 m^2, class 4 represents equal or larger than 90 m^2 but smaller than 110 m^2, class 5 represents equal or larger than 110 m^2 but smaller than 130 m^2, and class 6 represents equal or larger than 130 m^2.

Beyond the general household information, the second part of the survey collected information on the household water-use amount, energy consumption, and water end use facilities. Specifically this included family average monthly water-use amount; monthly consumed electricity; monthly gas consumption; power and energy efficiency class of various heaters, boiling pots, washing machines, drinking water machines;, and volume of toilet flushing box; possession of water-saving tap, water-saving bath shower, water-saving toilet.

The third section collected information on the frequency of water use and the water temperature of these uses. This detailed the number of times of taking showers and water temperature, number of times of face washing, feet washing, tooth brushing, hand washing, cloth washing and water temperature, drinking water amount and water temperature. Since specific water temperatures are far beyond the capacity of those who are inquired, the information collected only dictated whether cold water or hot water was used. In addition, we asked respondents to specify their behavior on water-use trends in summer and winter in order to analyze seasonal trends. Finally, we also asked if any households utilized recycled water resources, including recycling of water used during shower bath, recycling of water used for washing clothes, rice, and vegetables. The complete questionnaire is documented in Appendix 4.

4 Results and Discussion

4.1 Results of Sampling Survey

The distribution of effective respondents according to the number of family members is shown in Fig. 3 and the distribution of effective respondents according to the highest education level of family members is shown in Fig. 4.

On average monthly income, those families who chose below ¥4,000 (about 619 dollars) account for 13.3% of the total; those families who chose ¥4,000–7,000 (about 619–1,084 dollars) account for 27.6%, those families who chose ¥7,000–10,000 (about 1,084–1,548 dollars) account for 27.7% of the total, those families who chose ¥10,000–16,000 (about 1,548–2,477 dollars) account for 26.6% of the total, those families who chose above ¥16,000 (about 2,477 dollars) account for 13.3% of the total. The income distribution of sampling families is shown in Fig. 5, average monthly income of sampling families shows normal distribution.

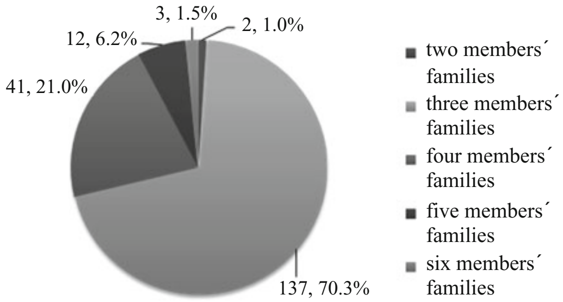

Fig. 3 Pie chart of the distribution of effective respondents according to the number of family members

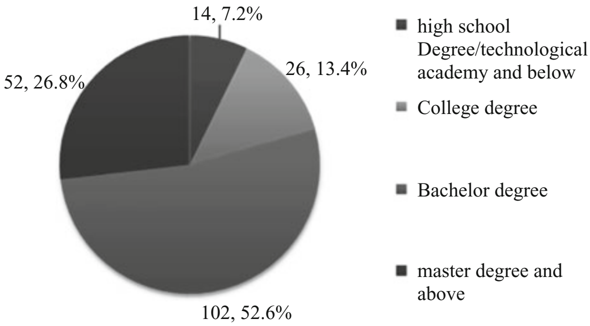

Fig. 4 Pie chart of the distribution of effective respondents according to the highest education level of family members

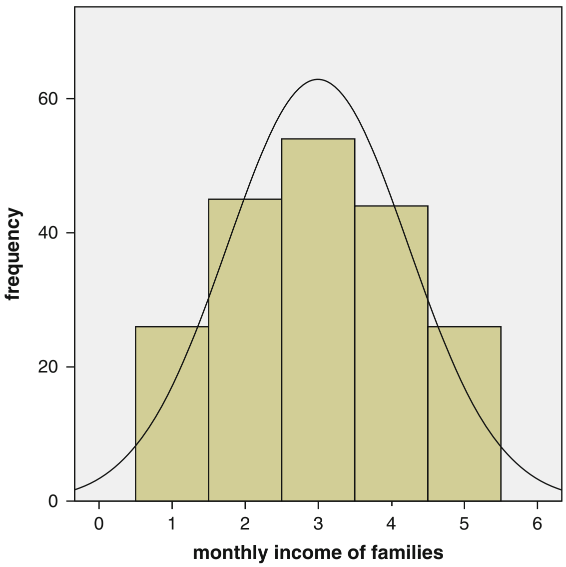

Fig. 5 Income distribution of monthly income of respondents versus frequency

In residential areas, the distribution of effective respondents according to the classification of household's residential areas is shown in Fig. 6. It is seen that families with households' residential area 70–90 m^2 (class 3) and 50–70 m^2 (class 2) are major parts, families with other area types are evenly distributed.

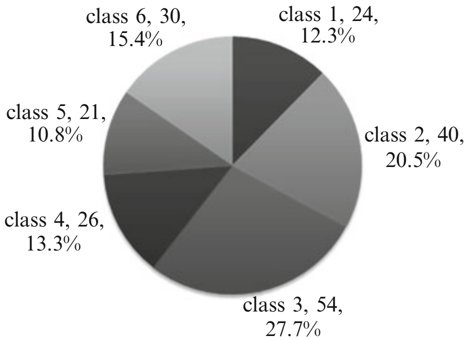

Fig. 6 Pie chart of the distribution of effective respondents according to the classification of household's residential areas

Table 4 Average value of per capita water intake in various family income levels

Family monthly income	Percentage of total respondents	Per capita households water intake [L/(per capita per day)]
1. Below $619	17.9	97.3
2. $619–1,084	23.1	106.0
3. $1,084–1,548	23.1	109.0
4. $1,548–2,477	22.6	113.8
5. Above $2,477	13.3	131.9

Table 5 Per capita household water intake on average

Types of residential areas	Percentage of the total sample	Households' water intake (L/per capita per day)
1. Below 50 m^2	12.3	98.1
2. 50–70 m^2	20.5	104.5
3. 70–90 m^2	27.7	108.5
4. 90–110 m^2	13.3	118.8
5. 110–130 m^2	10.8	134.4
6. Above 130 m^2	15.4	108.0

Per capita water intake is influenced by major factors such as family income, residential characters, and household water use [7–9]. Table 4 shows that as income rises, per capita daily water intake also rises in 195 household sampling. This reflects the trend of per capita water intake increase along with income increase.

The size of the residential area is a major factor, having impacts on households' daily water intake. In Table 5, average values of per capita households' water intake in various residential area types are shown. From type 1 to type 5, per capita households' water intake rises; however, in type 6, per capita water intake falls, compared with type 5.

The bigger the residential areas are, the more per capita the water use is needed for household cleaning. Those who live in bigger house in general enjoy higher living level with higher family income. However in type 6, per capita water intake reduced, this means the increasing trend of per capita water intake may not be linear. To a certain extent, the trend is reversed and impacts of residential areas on per capita water intake are limited. Further studies are going to be carried out on reasons of per capita value fall in type 6.

There are important impacts of water end use facilities on residential households' daily water intake. In questionnaires, washing machines, water-saving taps, water-saving bath showers and water-saving toilets were recorded.

In order to determine the significance of these water-saving devices, a correlation analysis was performed. The results concluded that there is insignificant correlation between water-saving tap, water-saving bath showers, water-saving toilets and reduction of per capita water intake. There is no significant difference between sampling family with water-saving facilities and those without water-saving facilities.

This lack of significance could be due to many reasons. First, some sampling families may not have been aware of the type of water-use fixtures in their homes. Water-saving policies pushed forward by Beijing municipality government are implemented in recent years, some government issued documents on water-saving fixtures, behaviors of design, purchase, use, production sale of water-use facilities under water-saving standards are banned in markets. Since 2005, all markets have only been selling water-saving fixtures. Residents may not be aware that their taps, bath showers, or toilets that they bought are water-saving.

Second, there could have been different understandings of water-saving fixtures, which may lead to some data in questionnaires misleading.

Third, impacts of water-saving fixtures are compensated by other influencing factors. Table 6 shows results of correlation analysis between water-saving fixtures and residential areas & recycling water-use level. In Question 25 of the questionnaire, choosing recycling of rice washing water, recycling of vegetable washing water, recycling of cloth washing water as credits, each positive choice gets one credit; credits are from lowest 0 to highest 3. Higher credits mean higher rate of water recycling. Those who live in big house with higher income prefer expensive water-saving toilet fixtures, so impacts of water-saving toilets are compensated by factors of large residential area, which needs more water for cleaning.

Besides, there is positive correlation between water-saving bath showers, water-saving taps and households' water recycling as shown in Table 6, families with water-saving bath showers and water-saving taps are tending to take water recycling in rice washing, vegetable washing, cloth washing, and bath water.

Water end use frequency plays an important role in water end use analysis; it is also a major factor in calculation and analysis of energy intensity of household water use. Questionnaires provide frequency of water end use, including number of times of average per capita bath shower taking, average per capita face washing, average per capita feet washing, average per capita teeth brushing, washing machine operations, households' cloth hand-washing, and drinking machine bottle replacing in a week (Table 7).

Temperature of different types of household water end use is another major factor influencing energy intensity of household water use (Table 8).

Table 6 Correlation of households' water-saving facilities with other factors

Spearman's rho		Types of residential areas	Water-saving toilet	Water-saving taps	Water-saving bath shower	Households' water recycling level
Types of residential areas	Correlation coefficient	1.000	0.216**	−0.089	0.083	−0.092
	Significance (two-tailed)		0.002	0.217	0.248	0.199
Water-saving toilet	Correlation coefficient	0.216**	1.000	0.188**	0.205**	0.062
	Significance (two-tailed)	0.002		0.008	0.004	0.386
Water-saving taps	Correlation coefficient	−0.089	0.188**	1.000	0.430**	0.295**
	Significance (two-tailed)	0.217	0.008		0.000	0.000
Water-saving bath showers	Correlation coefficient	0.083	0.205**	0.430**	1.000	0.213**
	Significance (two-tailed)	0.248	0.004	0.000		0.003
Households' water recycling level	Correlation coefficient	−0.092	0.062	0.295**	0.213**	1.000
	Significance (two-tailed)	0.199	0.386	0.000	0.003	

**Under 0.01 level, significant correlation (two-tailed test)

Table 7 Water-use frequency

Types of water end use		Water-use frequency Minimum	Maximum	Mean
Bath shower taking (time/per capita per week)	Summer	1	14	5.9
	Winter	1	7	3.0
Washing machine (times/week)	Summer	0	7	2.4
	Winter	0	7	2.0
Cloth hand-washing (times/week)	Summer	0	10	3.0
	Winter	0	7	0.7
Bottles of drinking water (bottles/week)	Summer	0.5	6	1.8
	Winter	0.3	6	1.6
Feet washing (times/per capita per week)	Summer	0	6	1.1
	Winter	0	7	4.0
Tooth brushing (times/day)[a]	–	1	4	2.0
Face washing (times/day)[a]	–	1	3	2.0

[a]No distinctive differences in the number of times of tooth brushing and face washing in summer and winter

As shown in Table 8, nearly 90% residents use cold water for face washing and teeth brushing in summer, but in the winter 60% residents use hot water for face washing and teeth brushing. For washing clothes, 92.8% families use cold water in

Table 8 Water temperature for various water end uses

Types of water end use		Cold water[a] (%)	Hot water (%)
Face washing and tooth brushing	Summer	89.7	10.3
	Winter	39.5	60.5
Feet washing	Summer	17.4	82.6
	Winter	1.0	99.0
Cloth hand-washing	Summer	92.8	7.2
	Winter	35.9	64.1

[a]Tap water in room temperature

Table 9 Types of household water recycle

	Percentage of respondents
Recycle of rice washing and vegetable washing water	61.5
Recycle of cloth washing water	45.6
Recycle of bath shower water	30.3

Table 10 Number of recycle types

	Percentage of respondents
No recycle	21.5
One type of recycle	36.4
Two types of recycle	25.1
Three types of recycle	16.9

summer, while in winter the percentage reduced to 35.9%. Most families choose hot water for feet washing, only in winter the percentage increases even higher, from summer' 82.6% to winter' 99%, which shows that people prefer higher temperature for feet washing.

Besides municipal reclaimed water supply for toilet flushing, residents in Beijing also preserve quality drainage of water used during bathing, cloth washing or rice and vegetable washing, toilet flushing, mopping floor or other domestic cleaning. Results of question No. 25 show water recycle situation in Beijing households preliminarily. In question No. 25, respondents were asked to choose from a list of options of recycling of rice washing and vegetable washing water, recycling of cloth washing water, and recycling of bath shower water according to their daily water-use behaviors. Percentages of respondents for three water recycling types and recycle type statistics are shown in Tables 9 and 10, respectively.

As shown in Table 9, recycling of water used for washing rice and vegetables is the most common, accounting for 61.5% of the total; recycling of water used for washing clothes accounts for 45.6% of the total; and finally re-using bath shower water only accounts for 30.3% of the total. This pinpoints bathing water as a target for future water-saving programs in Beijing since bath shower water accounts for the highest percentage in households' total water use.

There are 21.6% of respondents who do not recycle any water while 25.1% of respondents use two types of recycled water and 16.9% of respondents use three types of recycled water. This shows that Beijing residents have high consciousness in water saving.

4.2 Estimating Beijing's Energy Intensity of Household Water Use

4.2.1 Sources of Model Parameter Values

Based on formula (1), the calculation formula of energy intensity of household water use can also be expressed as below:

$$e_u = \sum_{i=1}^{n} \frac{E_{ui}}{Q_0} = \frac{\left(c_w \cdot \rho_w \cdot \sum_{i=1}^{n} Q_i \cdot \Delta T_i + f_l \cdot a \right)}{Q_0} = \frac{\left[c_w \cdot \rho_w \sum_{i=1}^{n} p \cdot f_i \cdot q_i \cdot (T_i - T_0) + f_l \cdot a \right]}{Q_0} \quad (2)$$

where e_u is the energy intensity of household water use, unit as kJ/m^3; i is the end use type of water; n is the total number of end use types of water in households; E_{ui} is the monthly energy consumed in water end use i, unit as kJ/month; Q_0 is the households' monthly water intake, unit as m^3/month; c_w is the heat capacity of water, its value as 4.2 kJ/(kg°C); ρ_w is the density of water, taken as 1 kg/L; Q_i is the monthly water intake of water end use i, unit as m^3/month; ΔT_i is the variation of temperature heated for water end use i; f_l is the monthly average frequency of washing machine operation, unit as working cycle/month; a is the rated consumed electricity of washing machine operation, unit as kJ/working cycle; p is the total number of family; f_i is the average monthly frequency of water end use i, unit as number per capita per month; q_i is the average volume of water end use i, unit as L per time; T_i is the temperature of water end use i; T_0 is the tap water temperature.

In this study, the values of average water intake and temperature of each type of household water use are calculated from data acquired from the actual measurement test of household water use in urban Beijing, while other variables are calculated from data in questionnaires. Sources of all variables of the model are listed in Table 11.

Since only few households indicated that their cleaning water was hot, it was assumed for this study that all household cleaning water was at room temperature and therefore yielded no energy consumption for heating.

Table 11 Parameters of the model of energy intensity of household water use

Variable	Meaning	Source
p	Family members	Questionnaires Q3
Q_0	Households' monthly water intake	Questionnaires Q7
F_1	Number of times of monthly bath showers per capita	Questionnaires Q15
F_2	Number of times of monthly face washing and teeth washing and feet washing per capita	Questionnaires Q16, Q18
$p{\cdot}f_3$	Number of times of households' monthly cloth hand-washing	Questionnaires Q17
Q_1	Average bath shower water intake each time	Case test: average bath shower water intake in four case families, in summer 42 L/time, in winter 58.4 L/time
Q_2	Average water intake in face washing and teeth brushing each time	Case test: average water intake in face washing and teeth brushing–face washing in summer 1.7 L/time, in winter 2.0 L/time; teeth brushing in summer 0.3 L/time, in winter 0.6 L/time; feet washing, in summer 3.9 L/time, in winter 4.1 L/time
Q_3	Average water intake in cloth hand-washing each time	Case test: average water intake in cloth hand-washing in four case families, 161 L/time
Q_4	Households' monthly drinking water	Case test: average drinking water in four case families; in summer 1.5 L/per capita per day, in winter 1.3 L/per capita per day
T_0	Outlet temperature of tap water	Case test: tap water outlet temperature in case families in summer average temperature from August 1 to 31, 27.7°C; in winters 14.8°C from December 1 to 31
T_1	Temperature of bath shower water	Case test: average temperature in bath shower water in four case families, in summer 39.4°C; in winter 41.9°C
T_2	Water temperature in face washing, teeth brushing, and feet washing	Q20–22 in questionnaires and case test: average water temperature of face washing, teeth brushing, and feet washing in four case families, in summer water temperature for face washing and teeth brushing 35.5°C, in winter 34.4°C; water temperature for feet washing in summer 42.5°C, in winter 42.7°C
T_3	Temperature in cloth hand-washing	Q23 in questionnaires and case test: hot water is chosen, the temperature average value 34.3°C in four case families in cloth hand-washing
T_4	Drinking water temperature	100°C
f_l	Number of times of monthly operation of washing machine	Questionnaires Q17

(continued)

Table 11 (continued)

Variable	Meaning	Source
a	Rated power of washing machine	Based on selection in Q10, according to types of washing machines (electricity consumption limitation and energy efficiency class of electrical washing machines) (GB12021-4-2004), in energy efficiency class 3, energy consumption of washing machine (washing capacity 5 kg), for drum washing machine 1.35 kWh/working cycle, for pulsate washing machine 0.11 kWh/working cycle

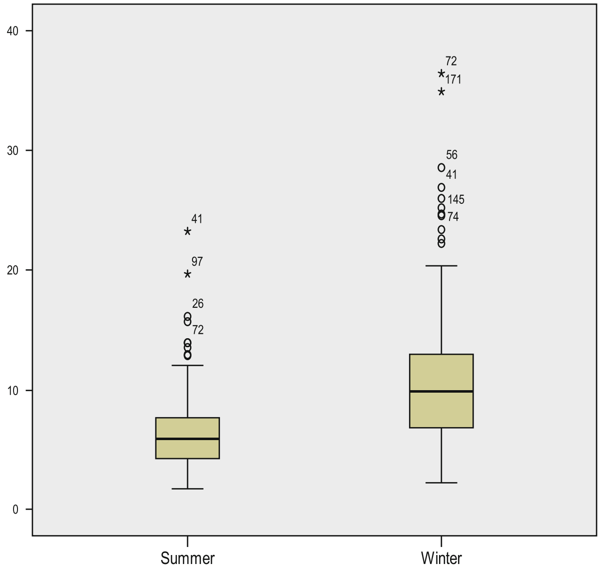

Fig. 7 Box plot of energy intensity of household water use of respondents

4.2.2 Descriptive Statistics Analysis

According to equation (2), energy intensity of household water use of each effective sampled family is calculated. Fig. 7 is the box plot of the energy intensity of those 195 effective respondents. As shown in Fig. 7, there are seven outliers in summer and eleven outliers in winter; their energy intensities are much larger than others. In order to eliminate the influence of outliers on overall judgment and statistical inference, outliers are excluded and 182 respondents remained. Following analysis is based on the remaining 182 respondents.

Based on Table 12, sampling mean of the energy intensity of the household water use in summer is 5.94 kWh/m^3, which includes 4.44 kWh for bath shower water use, 1.19 kWh for drinking water, 0.19 kWh for washing machine operation,

Table 12 Descriptive analysis on energy intensity of sampling households' water use in summer (unit: kWh/m^3)

	Sampling numbers	Minimum	Maximum	Mean	Standard deviation
Energy intensity of household water use, Including:	182	1.71	12.92	5.94	2.369
Energy consumption in bath shower water use	182	0.92	10.32	4.44	2.020
Energy consumption in face washing, teeth brushing, and feet washing water use	182	0.00	0.84	0.12	0.184
Energy consumption in cloth washing water use	182	0.00	3.78	0.19	0.458
Energy consumption in drinking water use	182	0.35	2.83	1.19	0.447

Table 13 Descriptive analysis on energy intensity of sampling households' water use in winter (unit: kWh/m^3)

	Sampling numbers	Minimum	Maximum	Mean	Standard deviation
Energy intensity of household water use, Including:	182	2.21	20.35	9.78	4.143
Energy consumption in bath shower water use	182	0.74	17.23	6.73	3.688
Energy consumption in face washing, teeth brushing, and feet washing water use	182	0.00	5.35	1.43	0.934
Energy consumption in cloth washing water use	182	0.00	3.78	0.40	0.577
Energy consumption in drinking water use	182	0.36	2.89	1.21	0.456

and 0.12 kWh for face washing, teeth brushing and feet washing. The sampling mean of energy consumption in households' water use is higher in the winter than it is in the summer. As shown in Table 13, the sampling mean of the energy consumption in households' water use in winter is 9.78 kWh/m^3, which is 65% higher than in the summer months. This includes 6.73 kWh in bath shower water use, 1.43 kWh for face washing, teeth brushing and feet washing, 0.40 kWh for washing machine operation, and 1.21 kWh for drinking water. These show that while summer' household water intake is higher than that in winter, winter's energy intensity of household water use is higher than that in summer.

Figure 8 shows energy intensity component in households' water use in summer and winter based on sampling means. Percentages of energy consuming in bath shower water in summer and in winter are close; in summer, bath shower and cloth washing consume less energy, so energy consuming in drinking water accounts for 20% of the total; in winter, percentage of energy consuming in face washing, teeth

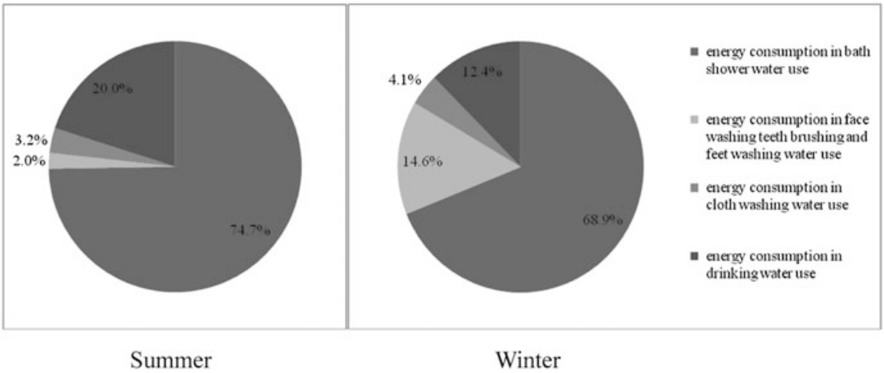

Fig. 8 Percentage of energy consumption by type

brushing, feet washing is up to 14.7%, percentage of energy consuming in drinking water is down to 12.4%; percentage of energy consuming in cloth washing in winter is 4.1%, a little higher than summer' 3.2%.

4.2.3 Statistical Inference

Statistical inference was carried out on energy intensity of household water use in Beijing, based on the abovementioned 182 respondents. In the process, energy intensity of household water use is studied in summer and in winter separately.

Normal Distribution Test

In order to implement statistical inference of the population of Beijing's households, it is necessary to understand the sample distribution. Only right distribution type is found, and then under theoretical probability formula, the statistical variable of the population at different probability levels could be calculated. As nhown in Fig. 9, the distribution of data of energy intensity of households' water use versus frequency is close to normal distribution in either summer or winter.

P–P plot and P–P trend plot of energy intensity of household water use in sample also show data versus frequency distribution comply with normal distribution, shown in Figs. 10 and 11.

Finally, K–S test was completed. K–S test is Kolmogorov–Smirnov test, put forward by former soviet scholars in 1930s, used for analysis on single set of samples, deduced sample set coming from certain known distribution, e.g. normal distribution, exponential distribution, Poisson distribution.

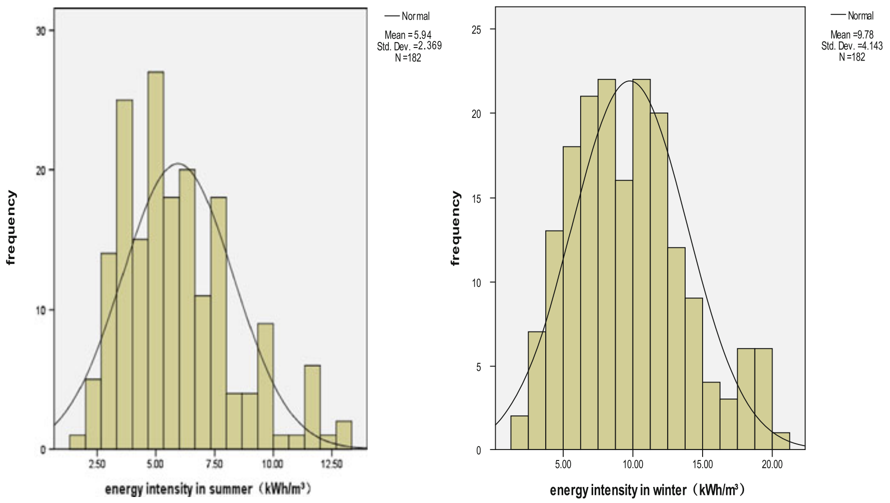

Fig. 9 Frequency of energy intensity of households' water use

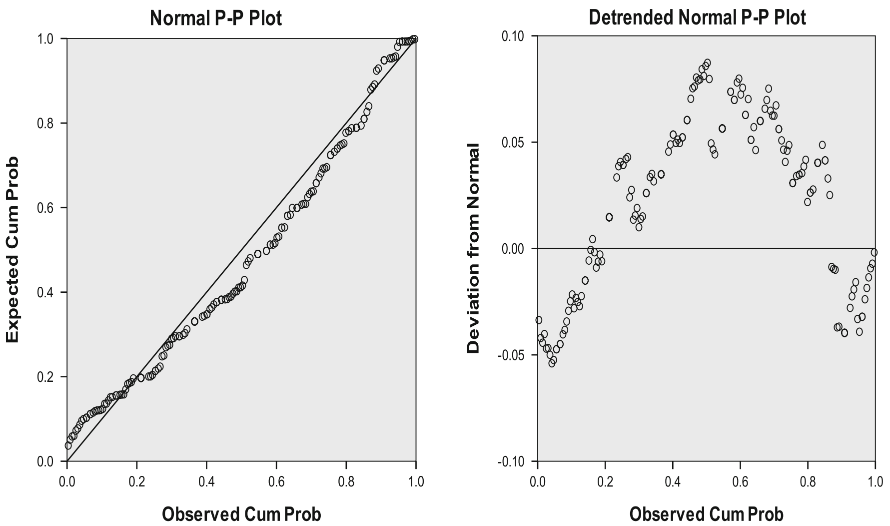

Fig. 10 Normal P–P plot and detrended normal P–P plot energy intensity of sampling households' water use in summer

The principle of K–S test is comparison of cumulative frequency distribution of observed samples with that of known theoretical distribution, maximum deviation is found, if samples comply with theoretical distribution, maximum deviation must not be high (i.e. probability in statistical test higher than certain significant level, usually significant level default is 0.05), otherwise samples not comply with theoretical distribution.

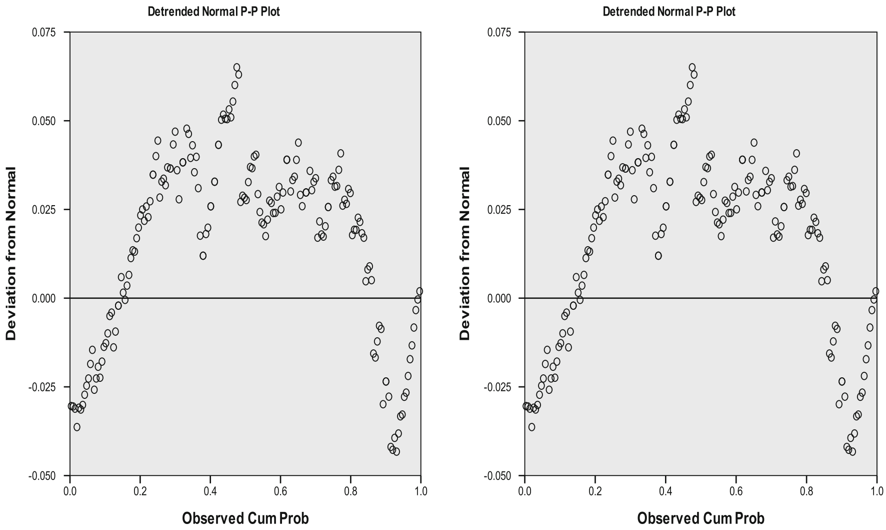

Fig. 11 Normal P–P plot and detrended normal P–P plot of energy intensity of sampling households' water use in winter

Table 14 K–S test in summer' energy intensity of household water use of the sample

N		182
Normal distribution data	Mean	5.94
	Deviation	2.37
Range	Absolute	0.090
	Positive range	0.090
	Negative range	−0.057
K–S test statistics *Z*		1.215
Two-tailed gradual probability *p*		0.105

Table 15 K–S test in winter' energy intensity of household water use of the sample

N		182
Normal distribution data	Mean	9.78
	Deviation	4.14
Range	Absolute	0.068
	Positive range	0.068
	Negative range	−0.045
K–S test statistics *Z*		0.914
Two-tailed gradual probability *p*		0.373

SPSS software is used to have K–S test on the sample of Beijing's households, results are shown in Tables 14 and 15. As shown in Tables 14 and 15, either in summer or in winter, the probability '*p*' of K–S test statistic '*z*' is larger than significant level 0.05, which proves that the sample and its population comply with normal distribution.

Table 16 Probability of Beijing's energy intensity of household water use

Probability (%)	Energy intensity (kWh/m^3)	
	Summer	Winter
20	3.95	6.30
30	4.70	7.61
40	5.34	8.73
50	5.94	9.78
60	6.54	10.83
70	7.18	11.95
80	7.93	13.26
90	8.98	15.09

Probability Calculation

Since these data exhibit normal distribution, the parameters of the normal distribution can be used to estimate the overall probability distribution.

Based on sampling mean and deviation, point estimation on overall mean and deviation of Beijing's energy intensity of household water use is 5.94 in summer, with deviation of 2.37; Beijing's energy intensity of household water use is 9.78 in winter with deviation 4.14.

Therefore, cumulative probability distribution function of Beijing's energy intensity of household water use in summer is:

$$F(x; 5.94, 2.37) = \frac{1}{2.37\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left(-\frac{(x-5.94)^2}{2 \times 2.37^2}\right) d_x. \quad (3)$$

Cumulative probability distribution function of Beijing's energy intensity of household water use in winter is:

$$F(x; 9.78, 4.14) = \frac{1}{4.14\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left(-\frac{(x-9.78)^2}{2 \times 4.14^2}\right) d_x. \quad (4)$$

Probability calculation results of Beijing's energy intensity of household water use are found in Table 16.

The computational results in Table 16 show Beijing's energy intensity of household water use under various probability levels. Taking 70% data as an example, data in the table indicate 70% of Beijing's urban households' energy intensity of household water use in summer smaller or equal to 7.18 kWh/m^3, in winter smaller or equal to 11.95 kWh/m^3.

Data at 50% probability level represent average level of Beijing's energy intensity of household water use: 5.94 kWh/m^3 in summer; 9.78 kWh/m^3 in winter. If differences in Beijing's energy intensity of household water use in spring and autumn are temporarily not taken into consideration, so as to impacts of different season's energy intensity on yearly average of energy intensity (understood as different weights in different seasons), just simply taking arithmetical mean of summer's energy intensity and winter' energy intensity as yearly mean of Beijing's energy intensity of household water use: 7.86 kWh/m^3, its connotation is 7.86 kWh (i.e. 28.3 MJ) energy consumed in Beijing' households' 1 m^3 water consumed. Based on this, 2010 Beijing' total energy consumed in 2010 Beijing' total household water use 6.21×10^8 m^3 is estimated as 4.88×10^9 kWh, that is 599.7 thousand TCE (Tons of Coal Equivalent[2]); accounting for 0.9% of 2010 Beijing' total energy consumption (66.688 million TCE).

The estimation shows that household water end use is involved in huge energy consumption, energy-saving effect in households' water saving plays an important role in saving urban energy consumption and reducing discharge.

In fact, considering energy consumed in kitchen water use is not involved in the paper, as well as transferred rate of heaters, the abovementioned energy intensity of household water use and percentage of energy consumed in household water use accounting Beijing' total energy consumption are on the lower side. As if heat efficiency of heaters assumed 90%, then Beijing' households' energy intensity at 50% probability level is 8.73 kWh/m^3, and the percentage of households' energy consumed in water use, accounting the total energy consumption of Beijing in 2010, is 1%.

5 Conclusions

This chapter provides a practical approach to estimate energy consumption in household water use and the results may help the public to be aware of the huge amount of energy consumption accompanying with their water use. Considering the energy calculated in this study did not include the kitchen hot water use, the actual share of energy consumed on household water use in total energy consumption of Beijing may be much higher than the estimation above. Moreover, if we want to see the complete water-energy nexus in cities' water use, the energy consumed in the process of water extraction, treatment, conveyance and wastewater treatment and recycling should be added in; meanwhile, other end users like commercial sector should also be incorporated in the analysis. Therefore, the total energy consumed in the artificial water system of Beijing is significant and have a much larger proportion of the city's overall energy consumption. In China, the departments of water administration can increase water-use efficiency by enhancing water demand management and promoting popularization of water saving and energy-saving appliances, as the governments perform a leading role in water supply and management and in the implementation of restrictions on market access of relevant water or energy using appliances.

However, it needs to be clarified that, as this area of Beijing' energy intensity of household water use is a whole new study area as well as restrained by limited capability in fund and manpower, the study in this chapter is only a preliminary attempt, may be useful as inspiration and references for future work. Further research could improve efforts by diversifying the representation level of the sampling survey and taking kitchen water use into account. This research showed that efficiency in the use of water, especially hot water in end users, has significant potential to decrease energy demand and thus reduce greenhouse gas emissions of cities and contribute to mitigate climate change.

Notes

1. 100 Yuan is about US$15.48, according to the average exchange rate of Yuan–dollar in 2011 in China Statistical Yearbook [6].
2. Based on Chinese Energy Statistics Yearbook, electricity converted into coal equivalent: 0.1229 kg/kWh, equivalent heat value means coal or oil equivalent released while in complete combustion [10].

Acknowledgments The authors would like to especially thank Xin-hui Li of Beijing's 13th Middle School and professor Ding-fa Gu of the Institute of Geographical Sciences and Natural Resources Research of CAS, who participated in the actual measurement tests of household water use and helped conduct sampling survey to get indispensable data for the study. We would also like to thank professor Xi-wu He of the Institute of Geographical Sciences and Natural Resources Research of CAS, who provided helpful suggestions and insight.

Appendix 1: Daily Water-Use Records

Date		Numbers in daytime	
Air temperature	°C	Relative humidity	%
Room temperature	°C	Tap outlet water temperature	°C
Hours of air conditioner operation	H	Times of flushing toilet used	次
Drinking water			
boiling water	L		
boiled water remained(in night)	L		

water used for shower bath					
	member(parents/student)	Heating time/s	°C Bath water temperature	Normal flow rate 10s/L	Bath time/s
1					
2					
……					

other water use				
		member	°C temperature /	Water volume/L
Tooth brush	1			
	……			
hand washing	1			
	……			
face washing	1			
	……			
feet washing	1			
	……			
Cloth hand-washing	1			water volume: numbers of cloth
	……			water volume number of cloth
cleaning(mopping, wiping tables)	1			
	……			
other uses ________	1			
	……			

conditions of water related equipments					
Washing machine		Water intake amount in one cycle/L	Numbers of water intake	°C Washing temperature	Washing time/minutes
	1				
	……				
Drinking water machine		Operation time(power on)	Hot water amount/L	Cool water amount/L	
	1				
	……				
Humidifier	1	Operating time hour			
	……	Operating time hour			
others	(please fill in types of equipments, operating times, hours, consumed KWh, water amount)				

Appendix 2: Family Background

Name		Tel.		Date	
Address				Floor	
Family members		Highest education level received of family member			
Relationship among family members					
Family annual income	□ under ¥50000	□ ¥50000-100000	□ ¥100000-200000	□ ¥200000-500000	□ Above □ ¥500000
Profession					
Hot water supply	□ centralized supply □family self supply				
Readings in electric meter before test		Reading in electric meter after test			
Reading in water gauge before test		Reading in water gauge after test			
Readings in gas meter before test		Reading in gas meter after test			

Appendix 3: Form of Households Water End Use Facilities

		Types of energy utilization(electric power/natural gas/solar energy)	Brand type	power(KW)/electricity in each working cycle(KWh)	(L)water amount used in each working cycle(L)
□heater	1				
	……				
□Electric pot/boiling pot	1				
	……				
□Washing machine	1				
	……				
□Drinking water machine	1			Heating power ：Cooling power	
	……				
□Humidifier	1			Power: Rated humidifying amount:	
	……				
□Toilet	1				
	……				

Appendix 4: Household Water Survey Questionnaire

Part 1 basic conditions

1. Your age: A. below 30 years old B. 30-45 years old C. 40-60 years old D. above 60 years old
2. highest education level received in your family members: A below senior high school/technical school B college C university D master degree and above
3. there are__members in your family, ___ persons below 6 years old, __persons above 60 years old, there are___ persons work, ___ persons in primary school, ___ persons in high school, ___ persons in college or university.
4. your family average monthly income:
   A. below ￥4000 B. ￥4000-7000 C. ￥7000-10000 D. ￥10000-16000
   E. above￥16000
5. your residence is: A. multi-floor building B. flat household C. chateau
6. your residence building area : ____m^2.

Part 2 household energy consumed and water end use facilities

7. Your family average monthly water use: ____tons; you think present water price:
   A. comparatively low B. medium C. comparatively high D. too high
8. Your family average monthly consumed electricity is ___kwh.
9. Your family average monthly consumed gas is ___m^3.
10. Is there any following electric appliance in your household?
   □ Electric pot/boiling pot, power:___, volume:___
   □drinking water machine, power:___ □little kitchen heater, power:___
   □electric heater □gas heater □solar heater □dish washing machine
   □humidifier □drum-type washing machine □pulsate-type washing machine
11. Is there any of the following water-saving facilities in your household?
   □Water-saving tap □water-saving bath shower □water-saving toilet
12. Your toilet:
   Amount of Sit type toilet is ___, water box is___L;
   Amount of squatting type toilet is ___, water box is___L.
13. Your washing machine: brand ___, type ___, ___ years old.
14. Your washing machine: energy efficiency standard star is ____, ___ power consumed each cycle, ___ water consumed each cycle, washing capacity is ___ kg.

Part 3 conditions of water end use

15. How many times in average each week your family member taking shower bath: ___ in summer, ___ in winter.

16. How many times in average your family member washing face every day:_____ in summer, ___ in winter.

    How many times in average your family member brushing teeth every day:_____ in summer, ___ in winter.

17. How many times in average your family doing laundry (including washing by hand and by washing machine) each week:____ in summer, ____ in winter; among these, how many times in average your family using washing machine each week: ____ in summer, ___ in winter.

18. How many times in average your family member washing feet each week: ___ in summer, ___ in winter.

19. How many times your family boiling water each week: _____ in summer, _____ in winter; each time ___ L.

Choose A or B in the following four questions: *A* stands for cool water, and *B* stands for hot water:

20. When washing face, your family members often use ___ in summer, ___ in winter.
21. When brushing teeth, your family members often use ___ in summer, ___ in winter.
22. When washing feet, your family members often use ___ in summer, ___ in winter.
23. When washing cloth, your family members often use ___ in summer, ___ in winter.
24. If you have drinking water machine, _____ barrels of water consumed each week in summer in average, and you usually drink ___ (A. cool water, B. hot water), ___ barrels of water consumed each week in winter in average, and you usually drink ___ (A. cool water, B. hot water).

Part 4 recycling of household water resources

25. Have your family the following behavior in water use:

    A. recycling rice washing water and vegetable water as mopping water and flushing toilet B. recycling cloth washing water C. recycling shower bath water

26. Have your family reclaimed water supply:

    A. yes, ___ tons are used in average monthly B. no

27. During shower bath, cool water discharged at the beginning is:

    A. discharged without recycle B. kept in barrel/basin for recycle

References

1. Cohen R, Nelson B, Wolff G (2004) Energy down the drain – the hidden costs of California's Water Supply. Natural Resources Defense Council, Oakland
2. Wilkinson RC (2000) Methodology for analysis of the energy intensity of California's Water Systems, and an assessment of multiple potential benefits through integrated water-energy efficiency measures. University of California, Environmental Studies Program, Santa Barbara
3. Kenway SJ, Priestley A, Cook S et al (2008) Energy use in the provision and consumption of urban water in Australia and New Zealand Water for a Healthy Flagship Report series ISSN: 1835-095X. CSIRO Australia and Water Services Association of Australia, Australia
4. Beijing Water Authority (2010) Beijing water resources bulletin. Beijing Water Authority, Beijing
5. Ministry of Housing and Urban–rural Development, P.R. China (2001–2010) China urban construction statistical yearbook. China Planning Press, Beijing
6. National Bureau of Statistics of China (2012) China statistical yearbook 2012. China Statistics Press, Beijing
7. Xiao-guang C, Jin-tao X, Yong-jie J (2007) Residential water demand analysis in North China (*in Chinese*). J Nat Resour Beijing 22(2):276–280
8. BSRIA (1998) Water consumption and conservation in buildings: potential for water conservation. BSRIA, USA
9. AWWA (1999) Residential end use of water. American Water Works Association and AWWA Research Foundation, USA
10. National Bureau of Statistics of China (2011) China energy statistics yearbook 2011. China Statistics Press, Beijing, 351

Reducing Carbon Footprint of Water Consumption: A Case Study of Water Conservation at a University Campus

Tammy E. Parece, Lawrence Grossman, and E. Scott Geller

Abstract This chapter reports on a study to promote environmentally relevant behavior on a university campus. Ten residence halls at Virginia Tech were included in the study, and the project employed five different strategies, each with a different number of prompting strategies to determine which approach was most effective at influencing reductions in water use. Consumption reductions were observed in most of the residence halls participating in the study, but no one strategy was more effective than another. Even though reductions were not achieved in all residence halls, overall water consumption was reduced by 11.6%. Reducing the consumption of water also resulted in the reduction of energy used to treat and transport the water from the University's water source – the New River. Therefore, the energy savings achieved resulted in a reduction of the University's carbon footprint.

Keywords Energy consumption, Environmentally relevant behavior, Natural resources, University residence halls, Water consumption

Contents

T.E. Parece (✉) and L. Grossman
Geography Department, Virginia Tech, Blacksburg, VA, USA
e-mail: tammyep@vt.edu

E.S. Geller
Center for Applied Behavior Systems, Virginia Tech, Blacksburg, VA, USA

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 199–218, DOI 10.1007/698_2013_227,

1 Introduction

The earth's surface is more than 70% water. Yet of the water on the planet, only 2.5% is freshwater and less than 0.1% is available for use. Water is a finite resource, and the 0.1% available for use is not evenly distributed over the earth's surface and further impacted by health and sustainability of the specific water body [1]. In the USA, water availability varies, from richness in the east to a dearth in the arid regions in the west.

Water is a basic necessity of life, and over the history of human existence, it has provided the means for expansion of human settlements around the world. Water shortages are occurring because of population growth and the expansion of settlements into more arid regions of the world. Currently, over one billion people in the world have insufficient water resources, and about 2.6 billion lack access to adequate sanitation [2]. As with other regions of the world, water availability in the USA is becoming an increasing concern [3].

Although the cause of climate change is a controversial topic, the temperature of the Earth's atmosphere is rising and climates are changing across the world [3]. These changes are affecting water resources from the melting of glaciers and ice sheets, rising sea levels, increased evapotranspiration from rising air temperatures, changing rainfall patterns, and intensified weather events [3].

Water resources and hydrologic processes are also affected by urbanization. Although urban expansion is attributed to increasing population, the rate of conversion to urban land uses far exceeds the rate of urban population increase [4, 5]. This landscape change, reducing vegetative cover and increasing impervious surfaces, alters the hydrologic cycle and affects water availability – less infiltration, higher runoff volume and rate, lower groundwater tables, decreased evapotranspiration [6], and precipitation anomalies [7]. Currently, over 50% of people, worldwide, live in urban areas; since this percentage is expected to rise to over 66% by 2050 [5], more water will be needed to meet this increase in number of urban residents.

The rate of natural resource consumption in the USA is the highest in the world. In the USA, an average family of four consumes 1,514 L of water per person per day from direct use [8]. But direct use does not include water consumed in the production of energy used by individual people, nor does it take into account virtual water – water used in the production, transportation, and consumption of material goods. For example, 3,407 L of water is required to make one pair of blue jeans [9]. The combination of increasing urban populations, increasing impervious surface cover, and additional stressors from climate change are affecting water availability around the world, even in water-rich areas such as the Eastern USA.

Human consumption rates reflect behaviors with significant environmental relevance as these rates both directly and indirectly affect natural resources [10, 11]. Consumption rates can be reduced by efficiency changes, which usually relate to one time or infrequent actions, and to changes in technology. Efficiency changes produce immediate reductions in consumption of natural resources. Examples include purchases of Water-Sense rated appliances, low flow showerheads and toilets, and on-demand hot-water heaters, but these efficiency approaches involve an upfront monetary cost.

Consumption rates can also be changed by curtailment initiatives. Curtailment focuses on reducing consumption through changing an individual's repetitive behavior, and experts argue that long-term sustainable reductions are achieved through modification of repetitive behavior [12–15]. But changing environmentally relevant behavior (ERB) is difficult in a society based on high consumption rates [15] and low-cost abundant water supplies [16]. Curtailment initiatives include activities such as taking showers instead of baths, taking shorter showers, and turning off water while shaving or brushing teeth.

This chapter reports on a study that examined how college students, residing on the Virginia Tech campus, responded to various strategies designed to promote ERB. Specifically, the research investigated the relationship between different forms of educational media and the consumption of water on Virginia Tech's main campus. In other words, we evaluated whether or not the water consumption behavior of students living in university residence halls would change in response to various conservation strategies. The strategies were applied at varying levels of intensity across five study groups over two semesters (spring and fall) in 2009. Additionally we explored whether one particular strategy would produce higher reductions in consumption, and whether combining strategies would produce more consumption reductions than individual techniques.

2 Study Site

Virginia Tech is located in the Town of Blacksburg, Virginia. It was established in 1872 as Virginia's first land grant college [17]. Virginia Tech and Blacksburg are located in a mountainous area of Southwest Virginia, about 610 m above sea level (Fig. 1) and are in the water-rich eastern USA.

Although located within a rural region of Virginia, the Town of Blacksburg is highly urbanized [20]. Virginia Tech's campus is also highly urbanized, and the campus environment is equivalent to a small city. After this study was completed, several additional buildings have been constructed on the campus, including residence halls and parking structures, and faculty, staff, and students have been added, evidence that urbanization is expanding, even in this rural locale.

As Table 1 shows, Virginia Tech's primary energy use represents 35% of the total primary energy use of Blacksburg. However, since Virginia Tech has a large

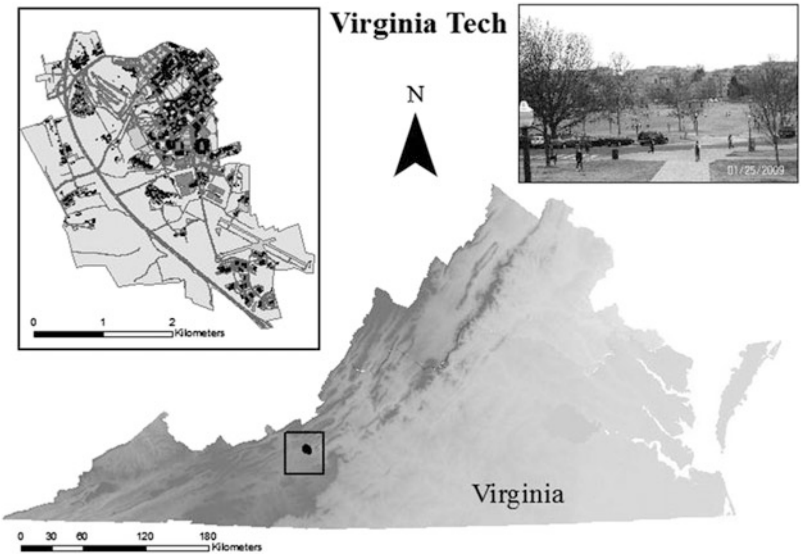

Fig. 1 Virginia Tech reference map ([18, 19], Photo by First Author)

Table 1 Virginia Tech and Blacksburg statistics during 2009

Characteristic	Statistic
Students residing on campus [K Belcher (2008) personal communication]	9,083
Average daily campus population [S Castle (2009) personal communication]	35,729
Number of buildings [19]	170
Number of residential buildings [19]	49
Area [19]	9.96 km^2
Percent of total area represented by impervious surfaces (calculated using ArcGIS 9.2 Vector Analysis Tools)	28%
Major energy resource [J Randolph, D Pitt (2007) unpublished]	Coal-fired steam power plants
Virignia Tech annual primary energy use [J Randolph, D Pitt (2007) unpublished]	3.0 TBtu[a]
Blacksburg annual primary energy use [J Randolph, D Pitt (2007) unpublished]	8.57 TBtu[a]

[a]Trillion British thermal unit

population that commutes daily to campus, primarily from within the Town, Virginia Tech's impact on energy use in Blacksburg is much higher.

Introducing resource-conserving strategies in such a university setting can be a challenge. Financial incentives in household-level energy studies have resulted in reductions in household-bills for energy use [21], but financial incentives are rarely a factor in household level water consumptions studies, likely because of the relatively low cost of water [16]. As with the 9,083 students residing on campus, commuters have no financial incentive to reduce resource consumption since they do not see a direct relationship between their consumption and their pocketbook.

Water for Blacksburg and Virginia Tech is pumped up from the New River through a 106.7-m lift, approximately 3.2 km to the water treatment facility (www.h2o4u.org). The treated water is then pumped to a high head storage tank, and afterwards delivered to Blacksburg and Virginia Tech using a booster pump station. The energy required for this delivery and treatment of water is estimated at 1.67 kWh per 3,785.4 L of water (1.67 kWh/3,785.4 L) [22]. The energy-use in Table 1 includes the energy required to deliver and treat the public water supply.

Estimating the carbon footprint for water consumption can be calculated from the carbon dioxide emissions from the fossil-fuel source used for the energy generated in treating and delivering the water [22]. As shown in Table 1, the energy generation in the Blacksburg area, and thus Virginia Tech's campus, comes mostly from coal. The U.S. Department of Energy estimates the carbon dioxide emissions from coal at 0.96 kg/kWh (as cited by Kloss [23]). The estimated savings in the carbon footprint related to reducing water consumption on Virginia Tech's campus can be calculated using the following equation [22]:

$$\begin{aligned}&\text{Carbon footprint reduction (kg of } CO_2)\\&\quad= \text{Water savings (L)} \times \text{Estimated energy use (kWh/3,785.4 L)}\\&\qquad\times CO_2 \text{ Output rate for coal (kg/kWh)}.\end{aligned} \tag{1}$$

3 Promoting ERB

To examine ERB and devise strategies to increase the occurrence of ERB, we reviewed perspectives from the relevant literature in psychological science, most specifically – social norm theory, value-belief norm theory, and the antecedent, behavior, consequence model (ABC Model) of applied behavior analysis.

Social norm theory argues that humans are social individuals who are influenced by interactions with other people. This theory is founded on the assumption that humans base their behavior on what is acceptable vs. unacceptable, and on those behaviors most frequently performed. If the unacceptable behavior is the behavior most frequently performed, people are most likely to conform to that behavior [24, 25]. Van Raaij and Verhallen [26], Kurz et al. [11], and Corral-Verdugo and Frías-Armenta [27] argue that whether or not people perform ERB are dependent on these social norms. Social norm theory is applicable to the research reported here because in a university's residence hall, interactions between students include communication and ERB relevant to defining acceptable behaviors. For example, students who see other students turning off water while brushing their teeth might be influenced to also turn off water while brushing their teeth.

Value-belief norm theory is also relevant to this research. Under this theory, ERB is prompted when people believe environmental issues threaten their values; they take action to alleviate this threat. This theory identifies three different categories of individual values: (1) egoistic, where people are focused on their own outcomes; (2) altruistic, or concern for others; and (3) biospheric/ecocentric concern for the nonhuman environment [28, 29]. University students exhibit egoistic values when they focus on attaining a positive outcome from their studies and seek stress relief during their free time.

This study considered altruistic and ecocentric values as students were informed on: (a) the causes of natural resource depletion, (b) the consequences of this depletion, (c) the impact of this depletion on their personal lives, (d) the threat of this depletion to their future, and (e) ways to reduce water use that allows them to maintain their current lifestyles while simultaneously sustaining natural resources for their future.

Another model widely discussed in the literature that can help refocus individual behavior is described by Geller [12] as the antecedent, behavior, consequence model (ABC Model) of applied behavior analysis. This model identifies ways to provide individuals with information on the causes of natural resource depletion, on how changing their behavior will lessen their impact on natural resources but not interfere with their lifestyle, and employs behavior-based techniques to increase the occurrence of repetitive ERBs. Antecedent strategies include:

- Information and education on (a) the rationale for ERB, (b) the impact of that behavior on natural resources, and (c) ways to reduce the adverse effects of resource-wasteful behavior; for example, washing clothes in cold water to reduce energy consumption;
- Prompts that specified a certain ERB to perform in a particular setting; for example, hanging tags on showerheads that asked residents to conserve water by limiting showering time (Fig. 2);
- Modeling or demonstrating a target ERB; for example, a student turning off water while shaving; and
- Commitment and goal-setting strategies relevant for a certain ERB; for example, a group agreement to reduce water use by 10% over prior usage.

Consequence strategies include:

- Feedback on the results of one or more ERBs; for example, reporting to residents the resulting decrease or increase in water usage after a particular intervention technique; and
- Rewards that support the target ERB, for example, a pizza party for those residence halls that reduced their water usage.

Researchers apply antecedent strategies in the early stages of ERB intervention. Consequence strategies might follow antecedent strategies at some point to reinforce the ERBs being promoted. Use of the strategies based on this model can alter individual values because participants realize their ERB allows them to maintain their egoistic values while also showing concern for others (altruistic) and the

Fig. 2 Shower hang tag

environment (ecocentric) with little impact on their own lifestyle. The theories and models related to increasing ERB are not limited to social norm theory, value-belief norm theory, or the ABC Model, but these are the most pertinent to the research reported here.

In promoting curtailment ERB initiatives, most experts agree that informing participants on the reasons for the target behavior is an integral part of any intervention plan, and prompts placed at the area where the activity should be performed help direct the desired behavior [30]. However, feedback is critical in maintaining ERB [31–33]. Feedback can take many forms – individual, comparative, or group – and whichever form is used, all researchers agree that it should be timed sufficiently to support the direct relationship between actions and results [26, 34].

While studies on household water consumption have been conducted (Table 2), gaps exist in the literature on research aimed at promoting water-related ERB of individuals at the institutional or organizational level. The majority of university studies focused on energy conservation; only two university studies involving water are evident in the literature (see Table 3). It is questionable whether colleges and universities are promoting or educating students that conservation of water is essential to sustainability. Torres-Antonini and Dunkel [48] reviewed 87 U.S.

Table 2 A selection of household-level water consumption research

Methodology	Targeted behavior	Locale
Efficiency changes [35][a]	Water conservation	East Brunswick Township, NJ
Efficiency[a], education, and feedback [30]	Water conservation	Blacksburg, VA
Feedback and goal setting [10]	Water and energy consumption	Eindhoven, Netherlands
Information and feedback [11]	Water and energy consumption	Perth, Australia
Survey [36]	Water conservation	Queensland, Australia
Interviews and questionnaires [37]	Water consumption	Sydney, Australia

[a]Efficiency changes refer to changes in technology and appliances, such as low flow showerheads and water saving toilets

Table 3 Studies in university settings

Methodology	Targeted behavior	Locale
Prompts and modeling [38]	Water-showering	University field house
Efficiency[a] and self development [39]	Electricity	Classrooms and residence halls
Information and then prompts [40]	Electricity	Classrooms
Efficiency changes [41][a]	Electricity	Office buildings and non-university residential
Efficiency changes [42][a]	Electricity	Residence halls and non-university residential
Prompts and feedback [43]	Recycling	Classrooms
Prompts and feedback [44]	Recycling	Classrooms
Education and social marketing [45]	Energy	Residence halls
Feedback [46]	Energy and water	Residence halls
Focus groups, observations, and surveys [47]	Energy conservation	Students, faculty, and staff

[a]Efficiency changes refer to changes in technology and appliances, such as hybrid vehicles and water and electricity saving devices

higher-education campus housing programs on sustainability – 32% of the programs included sustainability education – but reducing water use was related to efficiency changes and not curtailment initiatives.

4 Study Methodology

4.1 Design

To ensure similarity in water-use appliances, variation within the 49 campus residence halls was reviewed by using building characteristics – age, room design, renovation and remodeling history, and building usage with office space. Then, residents' characteristics were compared for similarities. Residence halls where occupants did not represent the general mix of campus student population, such as those housing the corps of cadets and athletes, were excluded from the study. After variability comparisons, the ten residence halls were divided into five different study groups using a random numbers table, each study group containing two buildings. These five designated study groups consisted of a Control Group and four intervention groups (Basic Information Group, Simple Feedback Group, Comparative Feedback Group, and Coaching Group). The inclusion of a control group was considered necessary to determine if the outcomes could be attributed to any influences besides the strategies employed.

Ten out of the 49 residential buildings, present on Virginia Tech's campus in 2009 (Table 1), were selected for this study. On-campus residential buildings are categorized into two groups – residence halls and Greek Houses (fraternities and sororities), but since the University could not track water consumption per building at the Greek Houses, this study only focused on the larger residence halls.

4.2 Intervention Strategies

Various strategies promoting ERB, as outlined in Table 4, were applied to each study group. The strategies relied particularly on those elements recommended by the ABC Model. The students in the control group residence halls were informed only that their residence hall was being included in a study on conservation of natural resources. The strategies used in the other four groups were additive in the sense that each subsequent study group received all of the techniques directed at the prior groups plus one additional technique. Employing the ABC Model's antecedent strategy of information, prompts and posters were placed within the residence halls of the four intervention groups prior to each semester.

Students in the Basic Information Group were advised of their inclusion in the study. Information was provided via email at the beginning of each month explaining how their actions contributed to the depletion of natural resources, why it was important to understand their contribution to this depletion, and a list of actions that they could take to reduce their water consumption. Students in the Simple Feedback Group were provided with all the strategies used by the Basic Information Group and were also provided monthly feedback on their water usage. An email sent within the first few days of each new month, reminded students of their inclusion in the study and provided them with results in the form of a percent reduction or percent increase in their previous month's water use as compared to the historical average for their residence hall. For those halls with decreases in water usage, the email congratulated them on their efforts and requested their continued contribution to conservation. The email also included a list of actions that they could take to continue their efforts to reduce water consumption.

Table 4 Study groups and strategies

	Control group	Basic information group	Simple feedback group	Comparative feedback group	Coaching group
Residence halls $n = 10$	2	2	2	2	2
Antecedent strategies used	Initial email advising of study	Initial email	Initial email	Initial email	Initial email
		Educational information	Educational information	Educational information	Educational information
		Prompts	Prompts	Prompts	Prompts
		Posters	Posters	Posters	Posters
		Periodic follow-up emails providing educational information	Periodic follow-up emails providing educational information	Periodic follow-up emails providing educational information	Periodic follow-up emails providing educational information
Consequence strategies used	None	None	Monthly feedback on their residence hall's results	Monthly feedback on their residence hall's results	Monthly feedback to team leaders on their residence hall's results
				Monthly feedback on how their residence hall's results compares to others halls in the study	Leaders within the halls to act as a coach to remind students of techniques to reduce consumption

Students in the Comparative Feedback Group received all the same strategies as the Simple Feedback Group. In addition, their monthly follow-up email contained information on how their residence hall's results compared with those of the other residence halls in the study.

Lastly, the students in the Coaching Group received all the strategies employed with the Comparative Feedback Group. In addition, several residents from the two residence halls in this group volunteered to assist with the study. These volunteers were asked for their assistance in displaying the informational posters, scheduling informational seminars, and acting as "coaches" – which involved reminding or demonstrating to other residents in their halls the ways to conserve water.

In the Spring Semester of 2009, meetings were held with three volunteers in each of the two residence halls in the Coaching Group. Educational seminars providing detailed information on the benefits of conserving natural resources were held for three of the residence halls during this semester. In addition, at the end of both Spring and Fall 2009 semesters, an email invitation was sent to the students in the four intervention groups, asking them to participate in a short survey to verify their participation in this study. The survey consisted of a list of actions that the students could take to reduce their consumption, such as reducing shower time and turning off the water while brushing their teeth or shaving. The students were asked to choose which actions they took during the intervention period.

Throughout both intervention semesters, visits were periodically made to all residence halls in the intervention groups to replace missing posters and prompts. One residence hall in the Control Group was excluded from this analysis for the Fall Semester 2009 due to construction and partial closing. Also, during the Fall 2009 Semester, no resident agreed to act as a volunteer in any of the residence halls.

Within 2 weeks of the start of the Spring semester, the study became contaminated when it became general campus knowledge that conservation research was taking place in the on-campus residence halls. This knowledge did not wane, because throughout both the Spring and Fall semesters, the project director (the senior author) was repeatedly contacted with requests for assistance in promoting water conservation in all university residence halls and ways to track their efforts. The project director was also asked by university administrators and student organizations to participate in meetings in an effort to promote water conservation after the study concluded.

The activities targeted in promoting ERB were activities within control of the students – such as washing full loads of clothes, turning off water while brushing teeth and shaving, taking shorter showers, and reporting water leaks.

University buildings are heated by steam but the university system tracking water use for steam heating is a separate system, so weather was not considered an artifact for this study.

4.3 Historical Water Usage

The University administration provided various data prior to and throughout the study period (Spring and Fall 2009) that were used to evaluate intervention impact. These data included records on 7 years of historical water usage (liters used per residence hall, per month) as well as the populations for each residence hall for each of those 7 years. The yearly population numbers were used for the monthly calculations, as the university does not track residence hall population changes on a monthly or semester basis. This information was used to standardize monthly usage per student in each residence hall for the baseline periods, calculated as follows:

For an individual year:

$$\text{Per student water use in liters} = \frac{\text{Monthly use in liters}}{\text{Residence hall population}}. \tag{2}$$

For average baseline usage:

$$\text{Student average monthly water usage per residence hall in liters (baseline usage)} = \frac{\Sigma \text{ all years derived from Eq. (2)}}{7}. \tag{3}$$

The university administration continued to provide monthly water meter readings for each residence hall in order to compare baseline water consumption vs. water consumption during the intervention periods, and provide monthly feedback to each residence hall in accordance with the particular intervention strategy. Equation (2) was used to calculate water usage per student for each month of the study in 2009. The change in water use was calculated as follows:

$$\frac{\text{2009 results} - \text{Eq. (3) results}}{\text{Eq. (3) results}} = \text{Percent increase } (+) \text{ or decrease } (-). \tag{4}$$

Throughout the study period, feedback to the residence halls in the Basic Feedback Group, the Comparative Feedback Group, and Coaching Group was sent to all students each month via email. The feedback provided was the percent change (either increase or decrease) in usage calculated using Eq. (4). Figure 3 is a sample of an email sent to a comparative feedback residence hall; a similar email was sent to the individual feedback group without the language “as compared to” other residence halls. A similar email was also sent to the Coaching Group with the additional information on the name of the coach within their hall. Each email was sent specific to each hall. For Sect. 5 of this chapter, we are reporting the results achieved over each entire semester, rather than a monthly basis.

Re: Results of Conserving Water and Electricity in XXXXXX

Dear XXXXXXXXX Student:

Thank you for taking part in our study on conserving water and electricity in your residence hall. Just a reminder, the study continues throughout the entire spring semester. Please continue your efforts in conserving water and electricity.

As promised, we are providing you with results of your efforts to conserve water and electricity.

For the period xxxxxxxxxxxxxxxx, as compared to your hall's usage in prior years, your hall *(X% reduction/increase/no change*) in consumption of water.

For the time period xxxxxxxxxxxxxxxxxxxx, as compared to your hall's usage in prior years, your hall *(X% reduction/increase/no change)* consumption of electricity.

Other residence halls in this study have achieved reductions in both water and electricity, so please continue your efforts at conserving natural resources.

Thank you again for participating in this study, we will continue to provide you with updates on your efforts to conserve water and electricity.

As a reminder, please conserve resources in your dorm in the following ways:

Please turn off all lights in unoccupied rooms.
Please turn off your computer when not in use.
Please turn off all power strips when not in use.
Please use task lights when available and not overhead lighting.
Please only wash full loads of laundry.
Please do not overload clothes dryers, clothes must tumble freely to dry efficiently.
Please wash clothes in cold water.
Please turn off the water while brushing your teeth.
Please turn off water while shaving.
Please limit the length of your shower to 5 minutes or less.
Please report any water leaks or running toilets immediately to maintenance.
If you leave for the weekend, please make sure all electronics are turned off in your room.
Over spring break, please turn off all appliances, including emptying and then turning off small refrigerators.

Notices are placed in significant locations in your residence hall to remind you of these various strategies to conserve natural resources.

Thank you for doing your part and for helping save our resources for your children.

Fig. 3 Sample follow-up comparative feedback email

4.4 Statistical Analyses

ANOVA test was considered the appropriate statistical test as we were interested in comparing the sample means of the intervention groups to each other in order to determine if any significant differences existed among those means, e.g., if combining strategies would produce more consumption reductions than individual techniques. The spring and fall data were kept separate because the same students did not necessarily reside in the same halls during both semesters as each semester was in a different school year.

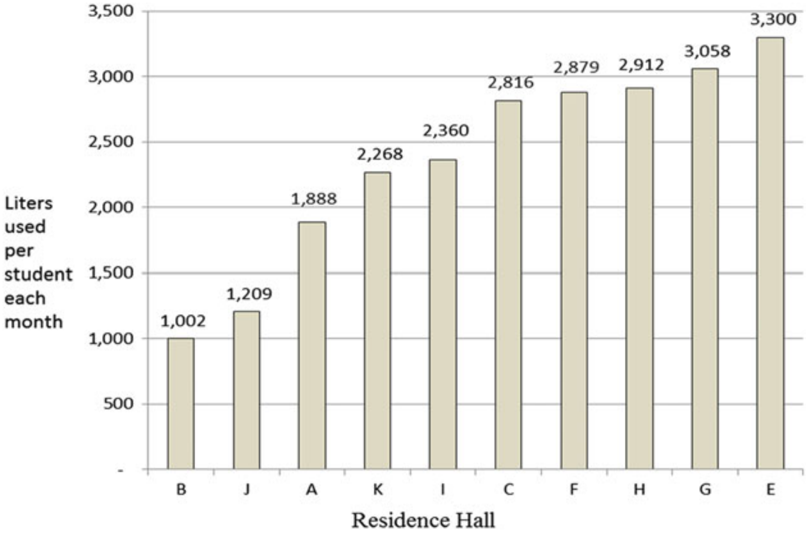

Fig. 4 Spring historical water usage – 7-year average (2002–2008)

5 Results and Discussion

5.1 Monthly Water Use per Student

By collecting data monthly and reporting these results monthly to the students in each residence hall throughout the study period, we were continually reminding the students of their inclusion in a study on ERB and providing them with timely information on their efforts to conserve water. Figure 4 depicts the Spring semester, 7-year historical average of water consumption by residence hall in liters used per student. The monthly historical consumption ranged from 1,002 L per student per month in Residence Hall B to 3,300 L per student per month in Residence Hall E. Table 5 documents the percent change in water usage per student during Spring semester 2009 as compared to the 7-year historical average (as calculated using Eq. (4)). The percentage change in water consumption ranged from a decrease of 18.1% in Residence Hall K to an increase of 17.5% in Residence Hall A. Reductions in water use were achieved in six of the ten halls in the study.

Figure 5 demonstrates the Fall semester 7-year historical average of water consumption by residence hall in liters used per student. The monthly historical consumption ranged from 1,072 L per student per month in Residence Hall B to 3,874 L per student per month in Residence Hall E. Table 6 documents the percent change in water use per student, Fall semester 2009 as compared to the 7-year historical average. The percentage change in water consumption ranged from a decrease of 32.6% in Residence Hall H to an increase of 8.1% in Residence Hall K. Reductions were achieved in six of the nine halls in the study.

Table 5 Percent change in per student water use, Spring 2009 versus historical average

Control group	Basic information group	Simple feedback group	Comparative feedback group	Coaching group
Dorm A	Dorm G	Dorm E	Dorm I	Dorm C
+17.5%	+6.3%	−2.3%	−4.7%	+12.7%
Dorm B	Dorm K	Dorm F	Dorm H	Dorm J
−11.2%	−18.1%	+0.7%	−14.5%	−15.9%

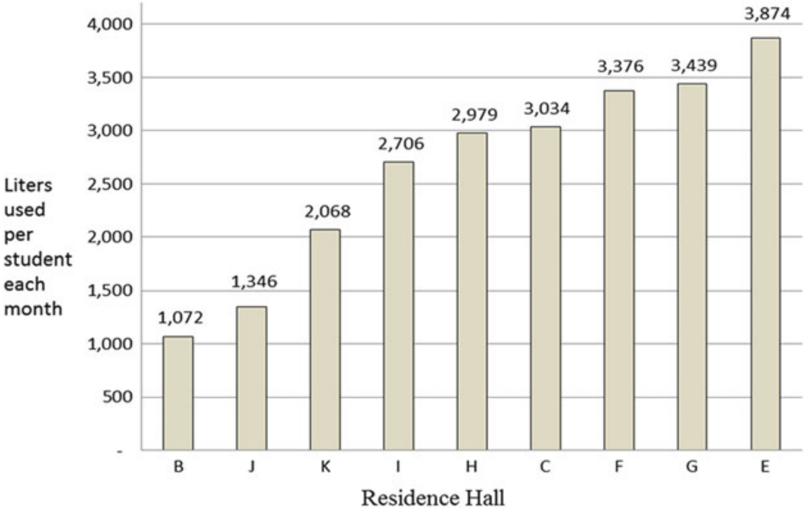

Fig. 5 Fall historical water usage – 7-year average (2002–2008)

Table 6 Percent change in per student water use, Fall 2009 versus historical average

Control group	Basic information group	Simple feedback group	Comparative feedback group	Coaching group
Dorm A	Dorm G	Dorm E	Dorm I	Dorm C
Excluded	−3.8%	+2.8%	−11.7%	+0.5%
Dorm B	Dorm K	Dorm F	Dorm H	Dorm J
−10.2%	+8.1%	−6.8%	−32.6%	−30.9%

5.2 Statistical Significance of the Intervention Strategies

For the examination of the statistical significance of any one particular intervention strategy over another, the data were analyzed separately for the two semesters. The analysis for the spring included ten residence halls, and that for the fall included nine residence halls.

The effects of the different types of behavior change strategies for the different study groups (Control Group, Basic Information Group, Simple Feedback Group,

Table 7 Analysis of variance by group – percent change in water use, Spring 2009

Source	DF	Sum of squares	Mean square	*F* ratio	$P > F$	R^2
Treatment type[a]	4	0.019	0.005	0.207	0.924	14.2
Error	5	0.117	0.0234			
C. total	9	0.136				

[a]Control group, basic information group, simple feedback group, comparative feedback group, coaching group

Table 8 Analysis of variance by group – percent change in water use, Fall 2009

Source	DF	Sum of squares	Mean square	*F* ratio	$P > F$	R^2
Treatment type[a]	4	0.077	0.019	0.927	0.529	48.1
Error	4	0.083	0.021			
C. total	8	0.160				

[a]Control group, basic information group, simple feedback group, comparative feedback group, coaching group

Comparative Feedback Group, Coaching Group) on the percentage change (increase or decrease) of water usage for the Spring 2009 semester were studied by a one-way analysis of variance of a balanced, completely randomized design with two residence halls in each group, for a total of ten residence halls (Table 7). At the $\alpha = 0.05$ significance level, there was no statistically significant evidence that percentage change in water consumption varied between the different study groups (Control Group, Basic Information Group, Simple Feedback Group, Comparative Feedback Group, Coaching Group) ($F = 0.207$, $P = 0.924$) during the Spring 2009 semester.

The effects of the different types of behavior-change interventions for the different study groups (Control Group, Basic Information Group, Simple Feedback Group, Comparative Feedback Group, Coaching Group) on the percentage change (increase or decrease) of water usage for the Fall 2009 semester were studied by a one-way analysis of variance of a completely randomized design with one residence hall in the control group and two residence halls in each intervention group, for a total of nine residence halls (Table 8). At the $\alpha = 0.05$ significance level, there was no statistically significant evidence that percentage change in water consumption varied between the different study groups (Control Group, Basic Information Group, Simple Feedback Group, Comparative Feedback Group, Coaching Group) ($F = 0.927$, $P = 0.529$) for the Fall 2009 semester.

5.3 End of Semester Surveys

During the last week of April and the first week of December, the students living in the target residence halls were invited to take a short survey to report on their conservation activities. The invitation was sent out to 2,828 students via email.

For the Spring Survey, 559 students responded (20% response rate), and of these, 431 students (77%) stated that they participated in conservation activities. The most common water-conservation activities were washing only full loads of clothes (89.8%) and turning off water while brushing teeth (88.8%).[1,2]

5.4 Carbon Footprint Reduction

The 7-year average of historical water use for the residence halls in this study was 80,122,694 L. The total water usage for these residence halls during the study period was 70,835,917 L for a total reduction of 9,286,777 l (11.6%). Using Eq. (1) to calculate the reduction in carbon as a result of the reduction in water use: Carbon footprint reduction (kilograms of CO_2) = 9,286,777 L $\times$ 1.67 kWh/3,785.4 L $\times$ 0.96 kg/kWh. A reduction of 4,097 kg of carbon emissions was achieved during the nine months of the intervention phase.

6 Conclusion

Although the literature supports the view that consequence strategies, such as feedback, are vital to successful impact on ERB, these consequence strategies did not reliably increase relevant ERB. Nonetheless, appealing individually to the students through the informational emails, posters, and prompts, our request to add altruistic and ecocentric foci to their values resulted in a positive response. That the students created a new social norm of conservation is evidenced by the 77% participation rate in conservation-related activities (as reported by the students in their answers to the Spring end of semester survey) and by the requests from students in those residence halls not included in the study asking if they could be included in the study. Social and value-belief norm theories were clearly applicable to the success of this study.

While we did not achieve consumption reductions in all residence halls, we did achieve reductions in the majority of the halls and those reductions resulted in an overall reduction in total usage. Additional intervention strategies did not produce any increase in consumption reductions. Better results were achieved in the Coaching Group residence halls during the second semester, so clearly the lack of a volunteer in these halls had no adverse effect on our study results. Notifying the

---

[1] No responses were obtained for the Fall Survey, possibly resulting from a glitch in the email invitation sent out by the University.

[2] Requests for additional information on the survey questions may be sent to the corresponding author at tammyep@vt.edu.

Control Group of their inclusion in the study also seems not to have impacted the study results since we had increases in one hall and decreases in the other.

Additionally, the reduction in water usage resulted in reduced energy usage and a reduced carbon footprint for the university. This study shows that college students can be educated on the need to reduce water consumption as part of ERB and that reduction can be achieved despite residing in a water-rich region and seeing no monetary impact when conserving resources.

Although Virginia Tech is located in a water-rich area, water is still a limited resource and increasing population density reduces per capita available water. Water shortages and water conflicts will soon follow without an understanding of the finite nature of water and the energy and water nexus. Adding these factors into sustainability education is necessary to facilitate an understanding on ways to reduce natural resource consumption and live sustainably.

In addition, universities and colleges are clearly interested in promoting sustainability on their campuses, evidenced by the number of institutions pledging to the American College and University Presidents' Climate Commitment. But studies or reports on the efforts and effects of institutions' efforts are still limited. Sharing this information with other universities and communities creates a collaborative effort at sustainability.

Acknowledgments We are grateful for the support of many officials at Virginia Tech and for the participation of numerous students. The Virginia Tech Graduate Student Assembly provided a Graduate Research Award which partially funded the purchase of intervention materials.

References

1. Knight JF, Voth ML (2012) Application of MODIS imagery for intra-annual water clarity 7 assessment of Minnesota Lakes. Rem Sens 4:2181–2198
2. WHO (2012) World health organization water sanitation and health. http://www.who.int/water_sanitation_health/mdg1/en/index.html Accessed 9 June 2012
3. IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Contribution of working group I to the 23 fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge and New York
4. Pickett STA, Cadenasso ML, Grove JM, Nilon CH, Pouyat RV, Zipperer WC, Costanza R (2001) Urban ecological systems: linking terrestrial ecological, physical, and socieoeconomic components of metropolitan areas. Annu Rev Ecol Syst 32:127–157
5. United Nations (2010) World urbanization prospects: the 2009 revision. Department of Economic and Social Affairs – Population Division. Available at http://esa.un.org/wpp/
6. Welker AL, Wadzuk BM, Traver RG (2010) Integration of education, scholarship, and service through stormwater management. J Contemp Water Res Educ 146:83–91
7. Geiger R, Aron RH, Todhunter P (2003) The climate near the ground, 6th edn. Rowman and Littlefield Publishers, Inc. Lanham
8. U.S. EPA (2012) Indoor water use in the United States http://www.epa.gov/watersense/pubs/indoor.html Accessed June 2012

9. Orange County Water District (2012) Water facts http://www.ocwd.com/ca-182.aspx Accessed 9 June 2012
10. McCalley LT, Midden CJH (2002) Energy conservation through product-integrated feedback: the roles of goal-setting and social orientation. J Econ Psychol 23(5):589–603
11. Kurz T, Donaghue N, Wakjer I (2005) Utilizing a social-ecological framework to promote water and energy conservation: a field experiment. J Appl Soc Psychol 35(6):1281–1300
12. Geller ES (1989) Applied behavior analysis and social marketing: an integration for environmental preservation. J Soc Issues 45(1):17–36
13. McKenzie-Mohr D (2000) Fostering sustainable behavior through community-based social marketing. Am Psychol 55(5):513–537
14. Lehman PK, Geller ES (2004) Behavior analysis and environmental protection: accomplishments and potential for more. Behav Soc Issues 13:13–32
15. Steg L, Dreijerink L, Abrahamse W (2006) Why are energy polices acceptable and effective? Environ Behav 38(1):92–111
16. Winkler RC (1982) Water conservation. In: Geller ES, Winett RA, Everett PB (eds) Preserving the environment: new strategies for behavior change. Pergamon, New York
17. Virginia Tech (2009) http://spec.lib.vt.edu/archives/125th/timeline.htm Accessed 13 February 2010
18. Commonwealth of Virginia (2002) GIS data. http://gisdata.virginia.gov/Portal/ Accessed 25 November 2009
19. Virginia Tech (2008) GIS layers provided by Virginia Tech facilities information system. Available for downloading at http://www.gis.lib.vt.edu/gis_data/Blacksburg/CDfiles.htm
20. Parece T, DiBetitto S, Sprague T, Younos T (2010) The Stroubles Creek watershed: history of development and chronicles of Research. VWRRC Special Report No. SR48-2010. Virginia Tech, Blacksburg. http://www.vwrrc.vt.edu/special_reports.html#2009
21. Abrahamse W, Steg L, Vlek C, Rothengatter T (2005) A review of intervention studies aimed at household energy conservation. J Environ Psychol 25(3):273–291
22. Younos T, Grady C, Chen T, Parece T (2009) Conventional and decentralized water supply infrastructure: energy consumption and carbon footprint. American Water Resources Association 2009 Spring Specialty Conference, Anchorage, May 4–6, 2009
23. Kloss C (2008) Managing wet weather with green infrastructure municipal handbook rainwater harvesting policies EPA-833-F-08-010
24. Cialdini RB (2003) Crafting normative messages to protect the environment. Curr Dir Psychol Sci 12(4):105–109
25. Schultz PW, Nolan J, Cialdini RB, Goldstein NJ, Griskevicius V (2007) The constructive, destructive, and reconstructive power of social norms. Psychol Sci 18(5):429–434
26. Van Raaij WF, Verhallen TMM (1983) A behavioral model of residential energy use. J Econ Psychol 3(1):39–63
27. Corral-Verdugo V, Frías-Armenta M (2006) Personal normative beliefs, antisocial behavior, and residential water conservation. Environ Behav 38(3):406–421
28. Stern PC, Dietz T, Abel T, Guagnano GA, Kalof L (1999) A value-belief-norm theory of support for social movements: the case of environmentalism. Res Human Ecol 6(2):81–97
29. Scherbaum CA, Popovich PM, Finlinson S (2008) Exploring individual-level factors related to employee energy-conservation behaviors at work. J Appl Soc Psychol 38(3):818–835
30. Geller ES, Erickson JB, Buttram BA (1983) Attempts to promote residential water conservation with educational, behavioral and engineering strategies. Popul Environ 6(2):96–112
31. Becker LJ (1978) Joint effect of feedback and goal setting on performance: a field study of residential energy conservation. J Appl Psychol 63(4):428–433
32. Stern PC, Gardner GT (1981) Psychological research and energy policy. Am Psychol 36 (4):329–342
33. Brandon G, Lewis A (1999) Reducing household energy consumption: a qualitative and quantitative field study. J Environ Psychol 19(1):75–85
34. Seligman C, Becker LJ, Darley JM (1981) Encouraging residential energy conservation through feedback. In: Baum A, Singer JE (eds) Advances in environmental psychology, vol 3. A. Baum and J. E. Singer, Hillsdale

35. Palmini DJ, Shelton TB (1982) Residential water conservation in a noncrisis setting: results of a New Jersey experiment. Water Resour Res 18(4):697–704
36. Miller E, Buys L (2008) The impact of social capital on residential water-affecting behaviors in a drought-prone Australian community. Soc Nat Res 21:244–257
37. Lawrence K, McManus P (2008) Towards household sustainability in Sydney? Impacts of two sustainable lifestyle workshop programs on water consumption in existing homes. Geogr Res 46(3):314–332
38. Aronson E, O'Leary M (1983) The relative effectiveness of models and prompts on energy conservation: a field experiment in a shower room. Environ Syst 12(3):219–224
39. McClelland L, Cook SW (1980) Energy conservation in university buildings: encouraging and evaluating reductions in occupants' electricity use. Eval Rev 4(1):119–132
40. Luyben PD (1980) Effects of informational prompts on energy conservation in college classrooms. J Appl Behav Anal 13(4):611–617
41. Wodarski JS (1982) National and state appeals for energy conservation: a behavioral analysis of effects. Behav Eng 7(4):119–130
42. Howard GS, Delgado E, Miller D, Gubbins S (1993) Transforming values into actions: ecological preservation through energy conservation. J Counsel Psychol 21(4):582–596
43. Larson ME, Houlihan D, Goernert PN (1995) Brief report: effects on informational feedback on aluminum can recycling. Behav Interv 10(2):111–117
44. Ludwig TD, Gray TW, Rowell A (1998) Increasing recycling in academic buildings: a systematic replication. J Appl Behav Anal 31(4):683–686
45. Marcell K, Agyeman J, Rappaport A (2004) Cooling the campus: experiences from a pilot study to reduce electricity use at Tufts University, USA, using social marketing methods. Int J Sustain High Educ 5(2):169–189
46. Petersen JE, Shunturov V, Janda K, Platt G, Weinberger K (2007) Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives. Int J Sustain High Educ 8(1):16–33
47. Marans RW, Edelstein JR (2010) The human dimension of energy conservation and sustainability: a case study of the University of Michigan's energy conservation program. Int J Sustain High Educ 11(1):6–18
48. Torres-Antonini M, Dunkel NW (2009) Green residence halls are here: current trends in sustainable campus housing. J Coll Univ Student Hous 36(1):10–23

Index

T. Younos and C.A. Grady (eds.), *Climate Change and Water Resources*,
Hdb Env Chem (2013) 25: 219–222, DOI 10.1007/698_2013,

Q

R

S

T

U

V

W

Y