

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS



27

# Climate Change Effects on Groundwater Resources

A Global Synthesis of Findings and Recommendations

Editors: Holger Treidel  
Jose Luis Martin-Bordes  
Jason J. Gurdak



A BALKEMA BOOK

INTERNATIONAL CONTRIBUTIONS TO HYDROGEOLOGY

27

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*Editors*

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*San Francisco State University, California, USA*



CRC Press

Taylor & Francis Group

Boca Raton London New York Leiden

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A BALKEMA BOOK

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© 2012 Taylor & Francis Group, London, UK

Typeset by MPS Limited, a Macmillan Company, Chennai, India  
Printed and bound by CPI Group (UK) Ltd, Croydon, CR0 4YY

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*Library of Congress Cataloging-in-Publication Data*

Climate change effects on groundwater resources : a global synthesis of findings and recommendations / editors: Holger Treidel, Jose Luis Martin-Bordes, Jason Gurdak. — 1st ed.  
p. cm.

Includes bibliographical references and index.

ISBN 978-0-415-68936-6 (hardback : alk. paper) 1. Groundwater. 2. Climatic changes—Environmental aspects—Case studies. I. Treidel, Holger. II. Martin-Bordes, José Luis. III. Gurdak, Jason J.

TD403.C576 2012  
553.7'9—dc23

2011036931

Published by: CRC Press/Balkema  
P.O. Box 447, 2300 AK Leiden, The Netherlands  
e-mail: Pub.NL@taylorandfrancis.com  
www.crcpress.com – www.taylorandfrancis.com – www.balkema.nl

ISBN: 978-0-415-68936-6 (Hardback)  
ISBN: 978-0-203-12076-7 (e-book)

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## ACKNOWLEDGMENTS

Compiling this book was a collaborative effort. We are sincerely grateful to all authors for their contributions. Their enthusiastic involvement and insightful feedback have allowed us to put together an interesting and valuable publication.

The preparation of this publication would have not been possible without the support of UNESCO's International Hydrological Programme (IHP) and its *Groundwater Resources Assessment under the Pressures of Humanity and Climate Change* (GRAPHIC) project, which has helped create an active and global group of scientists dedicated to unraveling groundwater and climate interactions and raising attention for a topic that has received only little attention previously. We would like to thank in particular Alice Aureli for her guidance and overall coordination and to Timothy Green for his continued support of the GRAPHIC expert group. Our thanks also go to the many cooperating universities, institutions, and organizations – too many to mention – that support GRAPHIC.

The Editors are grateful to the following people and many anonymous reviewers for their assistance with the external peer review of papers submitted for publication in this volume:

Giovanni Barrocu	University of Cagliari, Department of Land Engineering, Italy
John Bloomfield	British Geological Survey, UK
Elisabetta Carrara	Water Resource Assessment, Climate & Water Division/ Bureau of Meteorology, Melbourne, Australia
Dioni Cendon Sevilla	ANSTO Institute for Environmental Research, Australia
Jianyao Chen	Department of Water Resource and Environment, School of Geographical Science and Planning, Sun Yatsen University, China
Ian Ferguson	U.S. Bureau of Reclamation, Lakewood, Colorado, USA
Timothy Green	U.S. Department of Agriculture, Agricultural Systems Research Unit, USA
Ian Holman	Cranfield Water Science Institute (CWSI), Cranfield University, UK
Neno Kukuric	International Groundwater Resources Assessment Centre (IGRAC), The Netherlands
James Terry	Department of Geography, National University of Singapore, Kent Ridge, Singapore
Tristan Wellman	U.S. Geological Survey, Lakewood, Colorado, USA
Kamel Zouari	Laboratory of Radio-Analysis and Environment of the National School of Engineers, Sfax, Tunisia

# CHAPTER 1

## Introduction

### 1.1 RATIONALE

Groundwater is an essential part of the hydrological cycle and is a valuable natural resource providing the primary source of water for agriculture, domestic, and industrial uses in many countries. Groundwater is now a significant source of water for human consumption, supplying nearly half of all drinking water in the world (WWAP 2009) and around 43 percent of all water effectively consumed in irrigation (Siebert et al. 2010). Groundwater also is important for sustaining streams, lakes, wetlands, and ecosystems in many countries.

The use of groundwater has particular relevance to the availability of many potable-water supplies because groundwater has a capacity to balance large swings in precipitation and associated increased demands during drought and when surface water resources reach the limits of sustainability. During extended droughts the utilization of groundwater for irrigation is expected to increase, including the intensified use of non-renewable groundwater resources, which may impact the sustainability of the resource. However, global groundwater resources may be threatened by human activities and the uncertain consequences of climate change.

Global change encompasses changes in the characteristics of inter-related climate variables in space and time, and derived changes in terrestrial processes, including human activities that affect the environment. Changes in global climate are expected to affect the hydrological cycle, altering surface-water levels and groundwater recharge to aquifers with various other associated impacts on natural ecosystems and human activities. Also groundwater discharge, storage, saltwater intrusion, biogeochemical reactions, and chemical fate and transport may be modified by climate change. Although the most noticeable impacts of climate change could be changes in surface water levels and quality, there are potential effects on the quantity and quality of groundwater. While recognizing that groundwater is a major source of water across much of the world, particularly in rural areas in arid and semi-arid regions, the Intergovernmental Panel on Climate Change (IPCC) 3rd and 4th Assessment Reports state that there has been very little research on the potential effects of climate change (IPCC 2001, 2007; Bates 2008). In recent decades, a wide array of scientific research has been carried out to better understand how water resources might respond to global change (Green et al. 2011). Recent research has been focused predominantly on surface-water systems, due to their visibility, accessibility and more obvious recognition of surface waters being affected by global change. However, little is known about how subsurface waters in the vadose zone and groundwater might respond to climate change and affect the current availability and future sustainability of groundwater resources (UNESCO 2008). It is important to mention that in the past ten years the number of peer-reviewed journal paper publications addressing groundwater and climate change has increased considerably as shown in Fig. 1.1. Also only recently, water resources managers and politicians are progressively recognising the important role of groundwater resources in meeting the demands for drinking water, agricultural and industrial activities, and sustaining ecosystems, as well as in the adaptation to and mitigation of the impacts of climate change and coupled human activities (Green et al. 2011).

## 2 Introduction

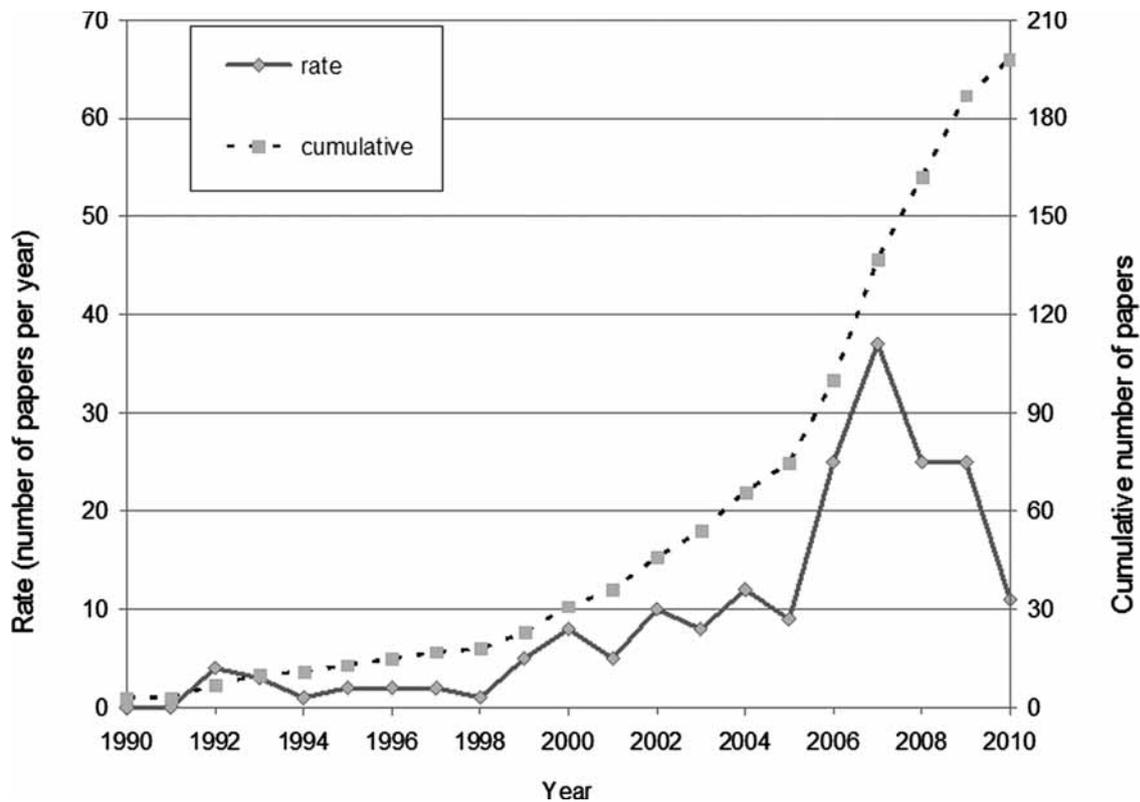


Figure 1.1. Rate of peer-reviewed journal paper publications addressing groundwater and climate change from 1990 to 2010. A total of 198 papers addressing subsurface water and climate change are included. Final references were compiled in February 2011, so some papers published late in 2010 may be missing (modified from Green et al. 2011).

Besides the direct impacts of climate change on the natural processes of the global hydrological cycle, it is crucial to also consider the indirect impacts. These are human responses to the direct impacts, such as increased utilization of groundwater in times of drought and non-availability of surface water and may lead to increased and unsustainable abstraction and utilization of groundwater resources, including non-renewable groundwater reserves. Thus, there are urgent and ongoing needs to address the expected coupled effects of human activities and climate change on global groundwater resources.

To address these concerns, the United Nations Educational, Scientific, and Cultural Organisation (UNESCO) International Hydrological Programme (IHP) initiated the GRAPHIC project (*Groundwater Resources Assessment under the Pressures of Humanity and Climate Change*) in 2004. GRAPHIC seeks to improve our understanding of how groundwater interacts within the global water cycle, supports ecosystems and humankind and, in turn, responds to complex and coupled pressures of human activities and climate change. To successfully achieve these objectives within a global context, GRAPHIC was developed to incorporate a collaborative effort and umbrella for international research and education. GRAPHIC outlines areas of desired international investigations covering major geographical regions, groundwater resource topics, and methods to help advance the combined knowledge needed to address scientific and social aspects (UNESCO 2008).

The GRAPHIC project was designed with the understanding that groundwater resources can have nonlinear responses to atmospheric conditions associated with climate change and/or terrestrial-surface conditions associated with human activities. Therefore,

groundwater assessments under the coupled pressures of human activities and climate change and variability involve the exploration of complex-system interactions. GRAPHIC incorporates a multidisciplinary scientific approach as the most rigorous platform to address such complexity. Furthermore, the GRAPHIC project extends investigations beyond physical, chemical, and biological interactions to include human systems of resource management and governmental policies. The structure of the GRAPHIC project has been divided into subjects, methods, and regions. The subjects encompass (i) groundwater quantity (recharge, discharge, and storage), (ii) quality, and (iii) management aspects. A variety of scientific methods and tools are being applied in the framework of GRAPHIC, including analysis of field data, geophysics, geochemistry, paleohydrology, remote sensing (in particular GRACE satellite gravimetry), information systems, modelling, and simulation. GRAPHIC consists of regional components (Africa, Asia and Oceania, Europe, Latin America, and the Caribbean and North America) where case studies have been identified and carried out.

The management of groundwater resources under the coupled pressures of climate change and human activities is a challenge. Sound understanding of the functioning of groundwater systems and their interactions with numerous and interlinked external factors is an indispensable basis for informed management. GRAPHIC strives to facilitate cooperation between scientists of different disciplines and from different countries. The basin/aquifer scale case studies presented in this book have been selected in each region by local scientists and experts of the respective subject.

## 1.2 OVERVIEW OF THE BOOK

*Climate Change Effects on Groundwater – A Global Synthesis of Findings and Recommendations* is a compilation of 20 case studies from more than 30 different countries that have been carried out under the framework of the UNESCO-IHP GRAPHIC project. The approximate location of each case study is displayed on the “Groundwater Resources of the World” map (WHYMAP 2008) (Fig 1.2).

The case studies presented in this volume represent aquifers from all the major climate regions of the world. The studies address groundwater resources in a range of hydrogeological settings from mountainous to coastal aquifer systems, including unconfined, semi-confined, and confined aquifers in unconsolidated to fractured-rock material. More details on each case study location, climate, hydrogeological setting, land use, groundwater use, as well as subjects addressed and methods applied are presented in the overview table (Table 1.1).

This volume is organized by case study according to the major climate groups of the Köppen-Geiger climate classification scheme (Köppen 1936): tropical, dry (arid and semi-arid), temperate, continental, and polar climates. Three chapters that cover several study areas and different climate groups are presented under “various climates” and are displayed in Figure 1.2 as one large circle or multiple circles indicating the regional scope of the respective chapter. The case study chapters (Chapters 2 to 21) each follow a similar organization and structure. The introduction of each chapter describes the purpose and scope, study area, methodology, and relevance to the GRAPHIC project. The results and discussion are followed by recommendations for water managers and planners, as well as policy and decision makers. Finally, the continuation of research activities and future work are outlined.

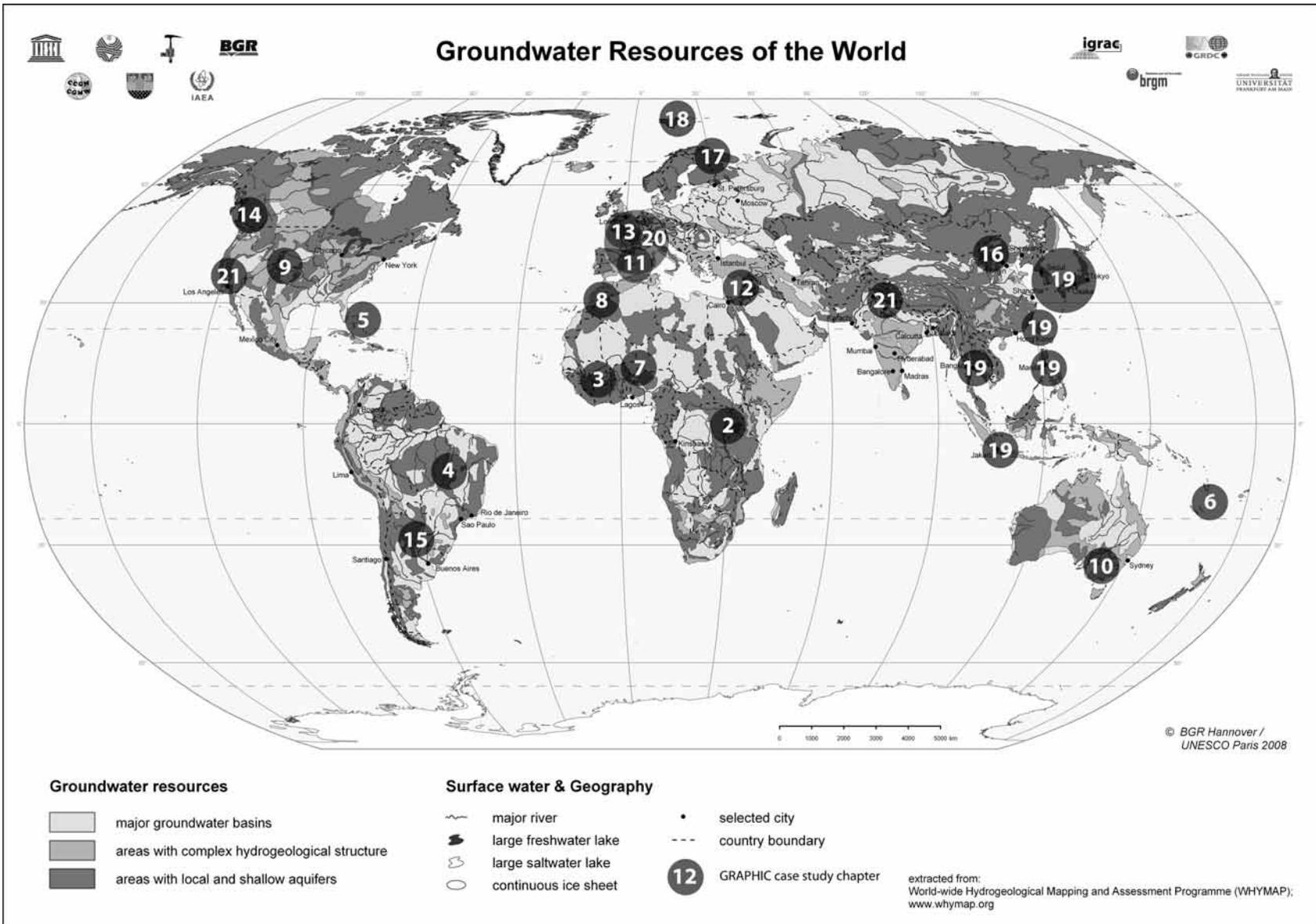


Figure 1.2. Approximate location of case study displayed on the “Groundwater Resources of the World” map (WHYMAP 2008). Numbers refer to the chapters in this volume. Case studies that cover several study areas and different climate groups are displayed as one large circle or multiple circles indicating the regional scope of the respective chapter.

Table 1.1 Overview of case studies.

Location	Climate	Hydrogeological setting	Land use	Groundwater use	Quantity or Quality	Methods
<b>Chapter 2: The Impacts of Climate Change and Rapid Development on Weathered Crystalline Rock Aquifer Systems in the Humid Tropics of sub-Saharan Africa: Evidence from South-Western Uganda</b>						
East Africa, South-western Uganda, River Mitano Basin	Tropical (humid)	Deeply weathered, crystalline rock aquifers	Agriculture, grassland, small areas of wetland, forest and plantations	Irrigation, livestock, drinking	<u>Quantity</u> : recharge, discharge, storage	Modelling
<b>Chapter 3: Groundwater Recharge and Storage Variability in Southern Mali, Africa</b>						
Western Sub-Saharan Africa, southern Mali, Niger river basin	Tropical (wet and dry), and partly dry (semiarid)	Clayey laterites overlying unconfined/semi-confined fractured sandstone aquifers	Savanna, shrubland, agriculture	Drinking, agriculture, livestock	<u>Quantity</u> : recharge, storage	GRACE, Modelling, Monitoring
<b>Chapter 4: Groundwater Discharge as Affected by Land Use Change in Small Catchments: A Hydrologic and Economic Case Study in Central Brazil</b>						
South America, central Brazil, Pípiripau river basin	Tropical (humid)	Deep, well drained soils (red oxisols and ultisols), underlain by quartzites, phyllites, and rhythmities	Agriculture, pastureland, natural savannah, woodland, grassland	Support aquatic ecosystems and hydrological services	<u>Quantity</u> : base flow discharge	Data correlation, empirical method
<b>Chapter 5: Effects of Storm Surges on Groundwater Resources, North Andros Island, Bahamas</b>						
The Caribbean, The Bahamas, North Andros Island	Tropical (humid)	Shallow, fresh groundwater lens in limestone and limesand aquifers	Forest, shrubland, rural communities	Local drinking and domestic needs; primary water supply for New Providence Island	<u>Quantity</u> : recharge, storage <u>Quality</u> : saltwater intrusion, salinity, septic systems	Monitoring

(Continued)

Table 1.1 Continued

**Chapter 6: Reducing Groundwater Vulnerability in Carbonate Island Countries in the Pacific**

Central and southern Pacific Ocean, small island nations	Tropical/Sub-Tropical	Shallow, fresh groundwater lens in permeable coral sand and karst limestone aquifers	Forest, shrubland, urban	Drinking, agriculture	<u>Quantity:</u> recharge, abstraction, storage; <u>Quality:</u> saltwater intrusion	Modelling, Monitoring
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**Chapter 7: Groundwater Resources Increase in the Iullemeden Basin, West Africa**

West Africa, Nigeria and Niger, Iullemeden Basin	Dry (semiarid)	Sedimentary basin, largely unconfined. Several confined aquifers exists at depth. (Continental Terminal aquifer – unconfined)	Mainly rainfed agriculture, livestock breeding (in the North)	Drinking, livestock breeding. Use for irrigation very limited spatially	<u>Quantity:</u> groundwater dynamics and recharge	Remote sensing, subsurface geophysics, environmental geochemistry hydrodynamics, monitoring, numerical modeling at various scales
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**Chapter 8: Climate Change and its Impacts on Groundwater Resources in Morocco: the Case of the Souss-Massa Basin**

North Africa, Morocco, Souss-Massa basin	Dry (arid to semiarid)	Shallow aquifer of the Souss-Massa plain, coastal aquifer	Irrigated agriculture	Irrigation, drinking, industry	<u>Quantity:</u> storage, recharge <u>Quality:</u> salinization, nitrate	Trend analyses (precipitation and temperature), monitoring (gw level), hydrochemical and isotopic tracers
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**Chapter 9: Vulnerability of Groundwater Quality to Human Activity and Climate Change and Variability, High Plains Aquifer, USA**

North America, central United States, Great Plains province	Dry (semiarid)	High Plains aquifer: primarily unconsolidated, unconfined aquifers	Irrigated and dryland agriculture, rangeland	Irrigation, livestock, drinking	<u>Quality:</u> nitrate, other chemical constituents <u>Quantity:</u> recharge, abstraction	Age dating, GIS, Modelling, Monitoring
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**Chapter 10: Groundwater Change in the Murray Basin from Long-Term In-Situ**

**Monitoring and GRACE Estimates (Australia)**

Southeastern Australia, Murray Basin	Dry (semiarid)	Unconsolidated sediments and sedimentary rocks. Confined and unconfined. Specific aquifers: Murray Group, Pliocene Sands aquifer, Shepparton Formation	Farming land, native and plantation forests, livestock production (cattle and sheep)	Irrigation, livestock, drinking	<u>Quantity:</u> recharge, discharge; <u>Quality:</u> salinization	GRACE, Monitoring
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**Chapter 11: Impact Assessment of Combined Climate and Management Scenarios on Groundwater Resources. The Inca-Sa Pobra Hydrogeological Unit (Majorca, Spain)**

Europe, Mediterranean Balearic island, Majorca, Spain	Mediterranean climate, temperate/semi-arid	Four different hydrostratigraphic units and three aquitard units, grouped into an upper and lower aquifer system	Agriculture	Irrigation, tourism, ecosystems	<u>Quantity:</u> recharge, discharge, exploitation	Modelling, simulations, management
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(Continued)

Table 1.1 Continued

**Chapter 12: The Effect of Climate and Sea Level Changes on Israeli Coastal Aquifers**

Mediterranean, coastal aquifers and Dead Sea, Israel	Mediterranean climate, dry (arid and semiarid)	Israeli coastal aquifer: inter-layered sandstone, calcareous sandstone, siltstone, and red loam Dead Sea coastal aquifer: Upper Cretaceous Judea Group Aquifer and the Quaternary alluvial coastal aquifer	Agriculture	Irrigation, domestic	<u>Quantity:</u> recharge <u>Quality:</u> saltwater intrusion, salinization	Modelling, simulations, monitoring
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**Chapter 13: Land Subsidence and Sea-Level Rise Threaten Freshwater Resources in the Coastal Groundwater System of the Rijnland Water Board, The Netherlands**

Europe, Coastal groundwater system, Rijnland, The Netherlands	Temperate, Continental	Quaternary deposits, intersected by loamy aquitards and overlain by a Holocene aquitard of clay and peat	Agriculture	Irrigation, domestic and industrial	<u>Quality:</u> saltwater intrusion, salinization	Modelling, simulations
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**Chapter 14: Climate Change Impacts on Valley-Bottom Aquifers in Mountain Regions: Case Studies from British Columbia, Canada**

North America, western Canada, mountain regions British Columbia	Dry (semi-arid to arid)	Okanagan Basin, Grand Forks: valley-bottom unconsolidated aquifers	Forest, shrubland, urban	Drinking, agriculture, industry	<u>Quantity:</u> recharge	GCM downscaling, Modelling, GIS
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**Chapter 15: Possible Effects of Climate Change on Groundwater Resources in the Central Region of Santa Fe Province, Argentina**

South America, Argentina, Santa Fe Province	Temperate (humid)	Upper unconfined aquifer: aeolian sedimentary deposits Semi-unconfined aquifer: sands of fluvial origin	Agriculture, livestock, rearing	Drinking, food production (agriculture, livestock rearing), industry	<u>Quantity:</u> recharge, discharge <u>Quality:</u> chemical compound input, salinization	Modelling
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**Chapter 16: Impacts of Drought on Groundwater Depletion in the Beijing Plain, China**

East Asia, China, Beijing Plain	Continental (dry)	Sedimentary (alluvial), shallow aquifer mainly unconfined, deep aquifers confined	Agriculture, industry, drinking	Irrigation from shallow aquifer; drinking, industry mainly from deep aquifer)	<u>Quantity:</u> recharge, storage	Monitoring, modelling
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**Chapter 17: Possible Effects of Climate Change on Hydrogeological Systems: Results from Research on Esker Aquifers in Northern Finland**

Europe, northern Finland	Continental (polar)	Esker aquifers: unconsolidated, unconfined or confined	Forest, peatland	Ecosystems, drinking, recreation	<u>Quantity:</u> recharge, discharge <u>Quality:</u> temperature, dissolved oxygen, salts	Monitoring, modelling
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**Chapter 18: Climate Change Effects on Groundwater in Permafrost Areas – Case Study from the Arctic Peninsula of Svalbard, Norway**

Europe, Norway, Svalbard peninsula	Polar (arctic)	Subpermafrost groundwater	none (60% covered by glaciers, large part is declared National Park)	Drinking (very limited)	<u>Quantity:</u> recharge, discharge	Monitoring, rock cores, simulation and modelling
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**Chapter 19: Groundwater Management in Asian Cities under the Pressures of Human Impacts and Climate Change**

Asian coastal cities: Tokyo, Osaka, Seoul, Taipei, Bangkok, Jakarta and Manila	Temperate, Continental Tropical	Coastal alluvial plain, urban subsurface soil	Urban	Domestic use, industry	<u>Quantity:</u> recharge, storage <u>Quality:</u> contamination	GRACE, modelling, GIS
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(Continued)

Table 1.1 Continued

**Chapter 20: Evaluation of Future Climate Change Impacts on European Groundwater Resources**

Northern and southern Europe, centred on the Å (Denmark), Medway (UK), Seine (France), Guadalquivir (Spain) and Po (Italy) river basins	Temperate, Continental Mediterranean	<u>River Å</u> : glacial sands and gravels <u>River Medway</u> : Cretaceous Chalk and Lower Cretaceous Sands <u>River Seine</u> : Cretaceous Chalk and Lower Cretaceous Sands <u>River Guadalquivir</u> : dolomitic limestone and alluvial deposits <u>River Po</u> : alluvial sediments	<u>River Å</u> : agriculture, industry <u>River Medway</u> : agriculture, pasture, urban <u>River Seine</u> : agriculture, urban, semi-urban <u>River Guadalquivir</u> : irrigated agriculture <u>River Po</u> : irrigated agriculture, urban, industry	Drinking water, irrigation	<u>Quantity</u> : recharge, water-stress	Modelling, simulations
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**Chapter 21: Sustainable Groundwater Management for Large Aquifer Systems: Tracking Depletion Rates from Space**

North America, western US, California, Central Valley aquifer; and northern India	Central Valley: Temperate (Mediterranean climate); northern India: Dry-Continental	Central Valley and northern India: confining units and unconfined, semiconfined, and confined aquifers	Agriculture	Irrigated agriculture, drinking, and industry	<u>Quantity</u> : discharge, storage	GRACE, monitoring, and modelling
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Tropical climate case studies (Chapters 2 to 6) include those from Africa (Uganda and Mali), Latin America (Brazil), the Caribbean (The Bahamas), and Pacific Island countries. Based on findings from south-western Uganda, Chapter 2 addresses whether intensive groundwater abstraction from weathered crystalline rock aquifers is a viable option to meet rapidly rising demand for domestic and agricultural water in Sub-Saharan Africa. The chapter also analyses projections of climate change impacts on groundwater resources and discusses opportunities and risks of their application to inform decision making. Chapter 3 describes the combined application of several methodologies, including measured field data, remote sensing, and modelling for estimating groundwater recharge and storage variability in southern Mali. The integration of these methods may be a promising tool for assessing groundwater resources in data scarce regions. The chapter also provides a preliminary assessment of the impacts of future climate change on groundwater recharge. The case study from Brazil (Chapter 4) uses an empirical method to assess the hydrological and economical effects of land-use change on groundwater discharge in a small tropical catchment.

Groundwater is the main source of freshwater on many islands. The resource is particularly vulnerable to extreme climate events, sea-level rise, and human-induced perturbations. Chapter 5 describes a storm surge from Hurricane Frances in 2004 that contaminated the groundwater supply on North Andros Island, The Bahamas. Chapter 6 presents key climatic, hydrogeological, physiographic, and management factors that influence groundwater quantity and saline intrusion into freshwater lenses beneath small Pacific Island countries.

Dry (arid and semiarid) climate case studies (Chapters 7 to 10) focus on the effects of climate change and human activities on groundwater resources in Africa (Morocco, Niger, and Nigeria), the United States (US), and Australia. Chapter 7 describes large-scale land clearing in the southern part of the Iullemeden Basin that experiences increased groundwater recharge and rising water levels over the past several decades. Management responses to outcropping water tables and salinization of soils are discussed. The Morocco case study (Chapter 8) analyses trends in temperature and precipitation and the effects of projected changes on groundwater recharge and water quality in the arid Souss-Massa Basin.

The quality of groundwater is often as critically important as its quantity in terms of groundwater sustainability. Chapter 9 presents the coupled effects of human and climate stresses on groundwater quality in the High Plains aquifer, which is the most heavily used aquifer in the US and supplies about 30% of the groundwater used for irrigation in the US. Focusing, in turn, mainly on groundwater quantity aspects, Chapter 10 shows the complex and coupled effects of human activity (land clearing) on groundwater (increase of recharge and groundwater levels), and subsequent multi-year drought (decrease of groundwater levels) in the Murray Basin in south-eastern Australia. A comparison of borehole data with space gravimetry (GRACE) and soil moisture estimates from hydrological models is used to test the capability of the GRACE mission and provide regional estimates of change in groundwater storage so that it can be applied for the monitoring of insufficiently instrumented regions.

Temperate climate case studies (Chapters 11 to 15) include those from coastal aquifers in Spain, Israel, and The Netherlands, mountain regions of British Columbia, and the Santa Fe Province of Argentina. The Mediterranean region faces an increasing water demand for agriculture and tourism, while climate change projections forecast an

increase of temperature, decrease of precipitation, and increased occurrence of extreme events. Chapter 11 analyses combinations of climate scenarios and management strategies on the island of Majorca (Spain) in view of preserving groundwater resources under predicted climate change.

Seawater intrusion into coastal aquifers is a concern in the Mediterranean. Chapter 12 describes the coupled effect of climate and anthropogenic sea level changes on Israeli coastal aquifers of the Mediterranean Sea and the Dead Sea. Chapter 13 presents the impacts of land subsidence and sea-level rise on freshwater resources in coastal groundwater systems of The Netherlands. In these systems, saline groundwater comes from the sea and from deep saline aquifers, and subsequently intrudes near-surface coastal groundwater systems. The salinization of the subsoil is caused by human-driven processes of land subsidence that have been going on for nearly a millennium.

Mountain watersheds or basins are unique high-relief environments that are important sources of water for local and downstream ecosystems and human population. Chapter 14 provides an overview of hydrogeological processes in temperate mountain regions as a basis for understanding how climate change may influence the groundwater systems. Case study examples of two valley-bottom aquifer systems in southern British Columbia, Canada highlight the complex interactions that need to be considered for climate change impact and adaptation assessment. Applying a modelling approach, the chapter explores recharge mechanisms and evaluates how the magnitude and timing of recharge may change under future climate conditions.

In the temperate central region of the Santa Fe Province in Argentina (Chapter 15) groundwater is the only source of water supply for all regional demands. The case study analyses available hydrogeological data to describe the aquifer system and quantify present groundwater availability. Future recharge to the aquifer system is estimated, and incorporated into a numerical groundwater flow model to assess future groundwater availability for drinking and food production under different climate scenarios.

Continental climate case studies (Chapters 16 and 17) include those from China and Finland. Chapter 16 analyses the impacts of prolonged drought on groundwater resources in the Beijing Plain where the combined effects of decreasing natural recharge and increasing abstraction have caused rapid depletion of groundwater storage. The chapter elaborates on direct and indirect impacts of climate change and proposes management responses based on simulations of groundwater depletion under various scenarios. Chapter 17 describes possible effects of climate change on esker aquifers in northern Finland. Eskers are an important source of potable groundwater in Finland and support many ecosystem services. However, groundwater in eskers is threatened by peatland drainage, agriculture, roads, and other land uses. This chapter describes the possible impacts of climate change and land use on esker groundwater systems with focus on the impact of peatland drainage in the esker discharge zone.

The polar climate case study (Chapter 18) is from Svalbard, Norway. Polar regions are sparsely populated, but have gained a lot of interest in the discussions about climate change because high-latitude areas are predicted to experience the most dramatic global climate change in this century. Moreover, large parts of these areas are regarded as pristine, with unique and highly specialized habitats for animals and plants. Groundwater forms part of this system that is – and will be – highly impacted by climate change. Chapter 18 presents a case study that examines climate change impacts on arctic sub-permafrost groundwater from the Arctic Peninsula of Svalbard, Norway.

Chapters 19 to 21 present case studies that encompass different climatic zones. Chapter 19 assesses the effects of climate change and human activities on urban subsurface environments and groundwater, which is an important but largely unexamined field of human-environment interactions. In this chapter, the subsurface environments of seven Asian coastal cities are studied with respect to water shortage, land subsidence, groundwater storage and contamination, thermal anomalies, and the urban heat island effect.

Similar to other regions of the world, groundwater in Europe is a substantial economic resource that is threatened by over-abstraction and contamination from surface-derived pollutants, which could be exacerbated by climate change. Chapter 20 evaluates future climate change effects on European groundwater resources in five study areas in northern and southern Europe, centred on the Å (Denmark), Medway (UK), Seine (France), Guadalquivir (Spain), and Po (Italy) river basins.

Chapter 21 describes the application of satellite gravimetry (GRACE) for characterizing groundwater storage changes in large aquifer systems – a method that provides new opportunities for water-resources monitoring, particularly in data sparse regions. Two case studies of groundwater depletion are presented, one in the relatively data-rich Central Valley aquifer of California (US) and in the other in more data-poor northern India.

The last chapter, Chapter 22, summarizes the main findings of the book in terms of new scientific insight and policy recommendations. This chapter, in particular, is expected to be of great interest to water resource managers, planners, and decision makers entrusted with the management of a valuable resource. In the light of global change, and climate change in particular, groundwater will continue to be an important resource that supports human health and livelihoods and many natural ecosystems. A sound understanding of the resource and current and future pressures from climate and human activities are necessary to guide adaptive management towards long-term groundwater sustainability.

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Climate change is expected to modify the hydrological cycle and affect freshwater resources. Groundwater is a critical source of fresh drinking water for almost half of the world's population and it also supplies irrigated agriculture. Groundwater is also important in sustaining streams, lakes, wetlands, and associated ecosystems. But despite this, knowledge about the impact of climate change on groundwater quantity and quality is limited.

Direct impacts of climate change on natural processes (groundwater recharge, discharge, storage, saltwater intrusion, biogeochemical reactions, chemical fate and transport) may be exacerbated by human activities (indirect impacts). Increased groundwater abstraction, for example, may be needed in areas with unsustainable or contaminated surface water resources caused by droughts and floods. Climate change effects on groundwater resources are, therefore, closely linked to other global change drivers, including population growth, urbanization and land-use change, coupled with other socio-economic and political trends. Groundwater response to global changes is a complex function that depends on climate change and variability, topography, aquifer characteristics, vegetation dynamics, and human activities.

This volume contains case studies from diverse aquifer systems, scientific methods, and climatic settings that have been conducted globally under the framework of the UNESCO-IHP project Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC). This book presents a current and global synthesis of scientific findings and policy recommendations for scientists, water managers and policy makers towards adaptive management of groundwater sustainability under future climate change and variability.



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