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

United Nations Educational, Scientific and Cultural Organization
International Hydrological Programme of UNESCO

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CLIMATE CHANGE EFFECTS ON GROUNDWATER RESOURCES

INTERNATIONAL CONTRIBUTIONS TO HYDROGEOLOGY

27

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ABOUT THE EDITORS

Holger Treidel is an environmental scientist and works as project coordinator with UNESCO's International Hydrological Programme in Paris. His work is related to the sustainable management of groundwater resources under the effects of climate change & variability, with particular focus on the complex challenges related to the management of transboundary aquifer systems. He is coordinating the UNESCO project Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) and global and regional transboundary groundwater management projects in cooperation with the Global Environmental Facility (GEF).

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Jason J. Gurdak is Assistant Professor of hydrogeology in the Department of Geosciences at San Francisco State University, California, USA. He and his research group address basic and applied questions about sustainable groundwater management, vadose zone and soil-water processes that affect recharge and contaminant transport, groundwater vulnerability to contamination and climate extremes, and the effects of climate change and interannual to multidecadal climate variability on water resources. Since 2004 he has served on the UNESCO project Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) that promotes science, education, and awareness of the coupled effects of climate change and human stresses on global groundwater resources.

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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).

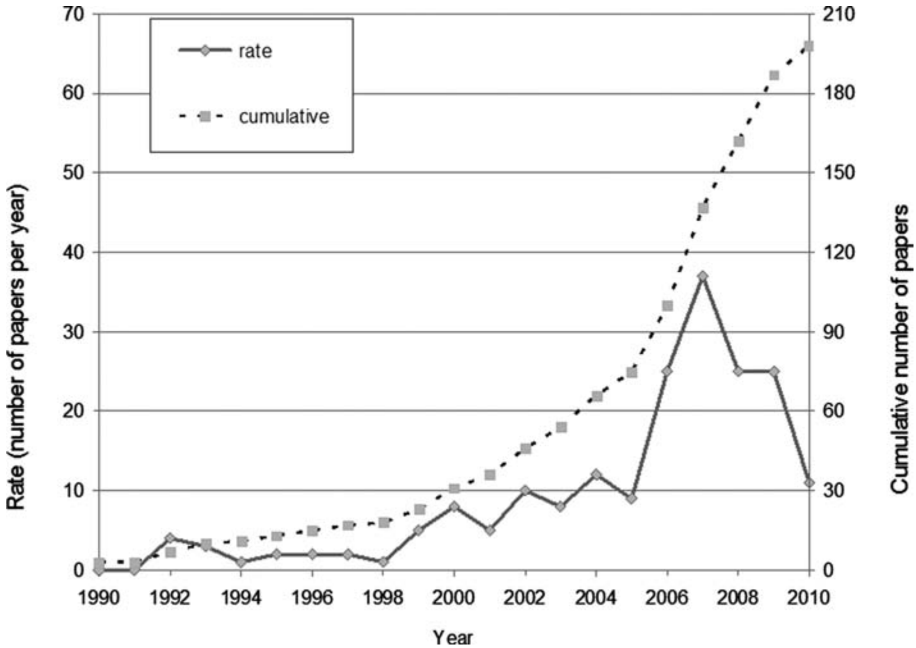

Figure 1.1. Rate of peer-reviewed journal paper publications addressing groundwater and climate change from 1990 to 2010. A total of 198 papers addressing subsurface water and climate change are included. Final references were compiled in February 2011, so some papers published late in 2010 may be missing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

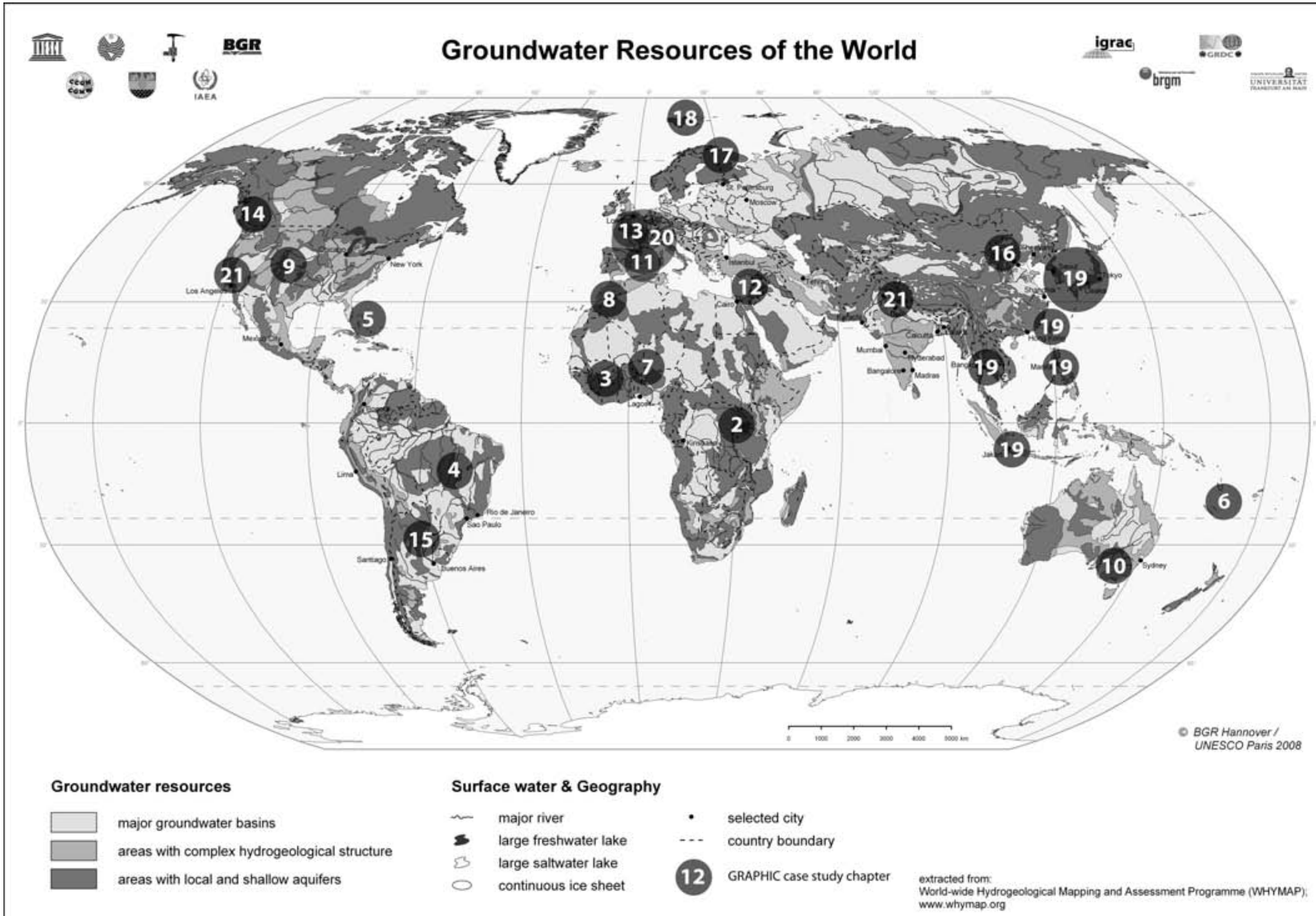

Figure 1.2. Approximate location of case study displayed on the "Groundwater Resources of the World" map (WHYMAP 2008). Numbers refer to the chapters in this volume. Case studies that cover several study areas and different climate groups are displayed as one large circle or multiple circles indicating 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
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						
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	Quantity: recharge, discharge, storage	Modelling
Chapter 3: Groundwater Recharge and Storage Variability in Southern Mali, Africa						
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	Quantity: recharge, storage	GRACE, Modelling, Monitoring
Chapter 4: Groundwater Discharge as Affected by Land Use Change in Small Catchments: A Hydrologic and Economic Case Study in Central Brazil						
South America, central Brazil, Pipiripau river basin	Tropical (humid)	Deep, well drained soils (red oxisols and ultisols), underlain by quartzites, phyllites, and rhythmites	Agriculture, pastureland, natural savannah, woodland, grassland	Support aquatic ecosystems and hydrological services	Quantity: base flow discharge	Data correlation, empirical method
Chapter 5: Effects of Storm Surges on Groundwater Resources, North Andros Island, Bahamas						
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	Quantity: recharge, storage Quality: 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	Quantity: recharge, abstraction, storage; Quality: saltwater intrusion	Modelling, Monitoring
Chapter 7: Groundwater Resources Increase in the Iullemmeden Basin, West Africa						
West Africa, Nigeria and Niger, Iullemmeden 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	Quantity: groundwater dynamics and recharge	Remote sensing, subsurface geophysics, environmental geochemistry hydrodynamics, monitoring, numerical modeling at various scales
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	Quantity: storage, recharge Quality: salinization, nitrate	Trend analyses (precipitation and temperature), monitoring (gw level), hydrochemical and isotopic tracers

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	Quality: nitrate, other chemical constituents Quantity: recharge, abstraction	Age dating, GIS, Modelling, Monitoring
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	Quantity: recharge, discharge; Quality: salinization	GRACE, Monitoring
Chapter 11: Impact Assessment of Combined Climate and Management Scenarios on Groundwater Resources. The Inca-Sa Pobla 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	Quantity: recharge, discharge, exploitation	Modelling, simulations, management

(*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
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
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
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

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)	Quantity: recharge, storage	Monitoring, modelling
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	Quantity: recharge, discharge Quality: temperature, dissolved oxygen, salts	Monitoring, modelling
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)	Quantity: recharge, discharge	Monitoring, rock cores, simulation and modelling
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	Quantity: recharge, storage Quality: contamination	GRACE, modelling, GIS

(*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	River Å: glacial sands and gravels River Medway: Cretaceous Chalk and Lower Cretaceous Sands River Seine: Cretaceous Chalk and Lower Cretaceous Sands River Guadalquivir: dolomitic limestone and alluvial deposits River Po: alluvial sediments	River Å: agriculture, industry River Medway: agriculture, pasture, urban River Seine: agriculture, urban, semi-urban River Guadalquivir irrigated agriculture River Po: irrigated agriculture, urban, industry	Drinking water, irrigation	Quantity: recharge, water-stress	Modelling, simulations
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	Quantity: discharge, storage	GRACE, monitoring, and modelling

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 Iullemmeden 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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Tropical Climates

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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

Richard Taylor & Callist Tindimugaya

ABSTRACT

Deeply weathered crystalline rock aquifer systems underlie much of the continental land masses in the tropics including sub-Saharan Africa, India and South America. Detailed catchment-scale studies in south-western Uganda reveal three key characteristics of the impacts of climate change and rapid development on weathered crystalline rock aquifer systems in the humid tropics. First, rapid development of groundwater resources is expected over the next two decades to have a more pronounced impact on groundwater resources than climate change. Second, projected changes in the seasonality and intensity of rainfall, though rarely considered, substantially influence the timing and magnitude of groundwater recharge. Third, quantified uncertainty in climate change impacts on groundwater discharges is substantial and arises primarily from the structure of general circulation models to simulate future rainfall and algorithms to estimate climate change impacts on potential evapotranspiration. In light of substantial uncertainty in current hydrological projections, groundwater management in the humid tropics will necessarily need to be adaptive and informed by groundwater and meteorological monitoring systems that reveal the response of groundwater systems to increased abstraction and climate change. A concerted, collaborative research effort between climate and water scientists is also required to reduce current uncertainty in hydrological projections; research in Uganda shows furthermore that employed models of groundwater recharge need to explicitly consider projected changes in rainfall intensity.

2.1 INTRODUCTION

2.1.1 Purpose and scope

The tropics[1] is home to ~40% of the world's population, the highest levels of population growth, and the majority of the world's poor. It is also where most of the sun's energy that drives global climate is absorbed and, as such, where changes in the water-holding capacity of the atmosphere as a result of anthropogenic warming are highest (Allen and Ingram 2002; Trenberth et al. 2003). Consequently, it is in the tropics where the impacts of rapid development and climate change on water resources are expected to be the most severe and where the need for sustainable adaptive management strategies in the water sector is greatest. Perversely, it is the tropics where the human and institutional capacity

[1] The region between latitudes 23.45°N and 23.45°S.

and hydrological knowledge base to devise adaptive water strategies are the most limited. Groundwater has for decades enabled communities across the tropics to adapt to seasonal or perennial shortages in surface water by providing water for drinking, watering livestock, and more recently irrigation. It is unclear, however, whether more intensive groundwater abstraction to meet rapidly rising demand for domestic and agricultural water is viable. Furthermore, a quantitative understanding of the impact of climate change on groundwater resources in the tropics remains elusive.

Large areas of the tropics including 40% of Sub-Saharan Africa (SSA) are underlain by deeply weathered crystalline rock aquifers (Taylor and Howard 2000; Maréchal et al. 2004; MacDonald et al. 2005). Aquifers comprising fractured bedrock (saprock) and a primarily *in situ* weathered, unconsolidated regolith (saprolite) possess low transmissivities typically ranging from 1 to $10\,m^2 \cdot day^{-1}$ (e.g. Houston and Lewis 1988; Howard et al. 1992; Briz-Kishore 1993; Owoade 1995; Chilton and Foster 1995) Higher transmissivities exceeding $10\,m^2 \cdot day^{-1}$ have recently been observed in tropical regoliths where alluvial and fluvio-laustrine deposits are present (Bradley 2011). Saprock and saprolite aquifers can operate as an integrated aquifer system wherein the overlying, more porous saprolite provides storage to underlying more transmissive fracture bedrock (Rushton and Weller 1985; Sekhar et al. 1994; Chilton and Foster 1995; Taylor and Howard 2000; Taylor et al. 2010). Further research is, however, required to resolve more completely the groundwater flowpaths and storage characteristics of this aquifer system.

In SSA, over half of the population depends in part or in whole on groundwater resources from saprolite-saprock aquifer systems for domestic water supplies. Of major concern is whether this aquifer system can sustain greater and more widespread groundwater withdrawals for rising domestic water demand and irrigation. The latter is recommended by both the Agricultural Water for Africa Initiative (AgWA) and Comprehensive Africa Agriculture Development Programme (CAADP) to improve food production and the resilience of the still predominantly rural population of small-scale farmers in SSA to climate variability and change.

At present, the duration and coverage of monitoring data for saprolite-saprock aquifer systems in the tropics are limited. With few exceptions (e.g. Groundwater Resilience in Africa[2]), research into these aquifer systems has focused on specific locations or basins (e.g. Nkotagu 1996; Taylor and Howard 2000; Maréchal et al. 2004; Giertz et al. 2006a) that are intended to be representative of more widespread hydrogeological conditions in saprolite and saprock aquifers. Here, we review evidence from a series of recent studies focused on the River Mitano Basin (Tindimugaya 2008; Mileham et al. 2008, 2009; Kingston et al. 2009; Kingston and Taylor 2010) of south-western Uganda which features the longest continuous record of daily river discharge in Uganda (1965 to present) and a time series of groundwater level and abstraction observations. Following a description of the basin, we describe three key outcomes from this research regarding the impacts of rapid development and climate change on groundwater resources in saprolite-saprock aquifer systems of the humid tropics.

2.1.2 Description of the study area: the River Mitano Basin

The River Mitano Basin is located within the humid, inner tropics just south of the equator in south-western Uganda (Fig. 2.1a). The basin is underlain by deeply weathered

[2]www.bgs.ac.uk/gwresilience

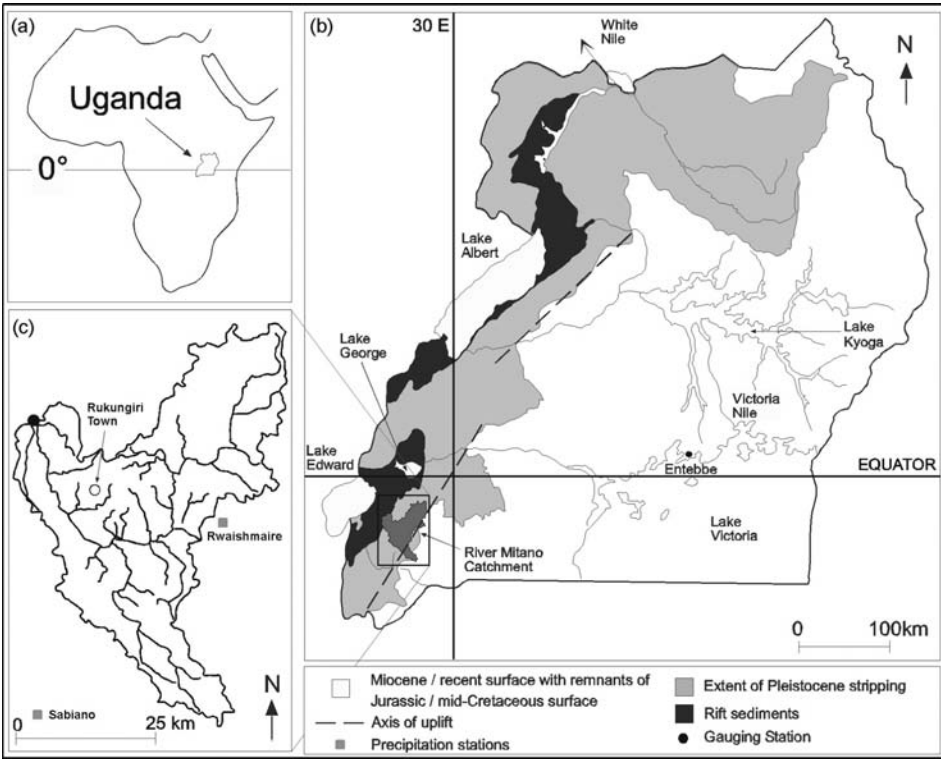

Figure 2.1. (a) Location of Uganda; (b) location of the basin within the weathered land surfaces of Uganda (Taylor & Howard, 1999a); and (c) map of the catchment drainage system showing gauging stations.

Precambrian crystalline rocks including gneisses, schists, phyllites and granites. The River Mitano flows in a north-westerly direction from upland areas, 2500 m above mean sea level (mamsl) in the south of the catchment, to the depression (graben) containing Lake Edward (975 mamsl) in the western arm of the East African Rift (Fig. 2.1b–c). The river's gauging station, located 20 km upstream of Lake Edward, represents an area of 2098 km^2. Detailed descriptions of the basin's geology, geomorphology and hydro-climatology are given in Tindimugaya (2008), Mileham et al. (2009), and Kingston and Taylor (2010). The weathered overburden (or regolith) comprises commonly truncated profiles composed primarily of coarse, less weathered material and there are frequent exposures of the Precambrian bedrock (Taylor and Howard 1999a). Fractures within the bedrock have developed from regional tectonic activity associated with rifting and more commonly from isostatic uplift resulting from the long-term weathering processes (Taylor and Howard 2000; Tindimugaya 2008). Groundwater from the weathered overburden (where it exists) and underlying fractured bedrock commonly form an integrated aquifer system that discharges into the River Mitano drainage network. The basin's high relief and incised drainage reflect, however, a runoff-dominated regime (Taylor and Howard 1999b). Land use is primarily agrarian (79%). Principal crops are millet, cassava, sugarcane, simsim, maize, groundnuts, soybeans, bananas, rice, maize, cotton, coffee and tobacco. Grassland dominates the remainder of the catchment (17%) with small areas of wetland (3%), forest and plantations.

Similar to other humid equatorial environments, the River Mitano basin experiences a bi-modal rainfall regime in which the dominant modes (wet seasons) occur in March–May (MAM) and September–November (SON) as a result of the movement of the Inner-Tropical Convergence Zone (Fig. 2.2). Mean annual catchment precipitation observed between 1965 and 1979 ranges from 963 mm in the east at Rwaishmaire to 1699 mm in the southwest at Sabiano (Fig. 2.1c). Mean annual pan evaporation observed over the period 1967–1977 at Mbarara, approximately 50 km to the east of the catchment, is 1535 mm. Monthly pan evaporation is relatively constant throughout the year, varying by less than 15% and exceeds precipitation in all months except peak wet season precipitation. Diurnal mean temperatures range from 13 to 26°C and this range is significantly greater than the variation (2°C) in mean monthly maximum and minimum temperature. Discharge records (1965–1979) for the River Mitano reflect bi-modal precipitation (Fig. 2.2) but lag peak precipitation by approximately 2 to 6 weeks. Mean river discharge is highest during SON ($35\,m^3 \cdot s^{-1}$, equivalent to a specific discharge of $520\,mm \cdot a^{-1}$) and lowest during the dry season after MAM ($6\,m^3 \cdot s^{-1}$, equivalent to $90\,mm \cdot a^{-1}$).

Both the regolith and fractured bedrock form relatively weak aquifers. Of 51 tested wells in the basin, well yields range from 0.1 to $23\,m^3 \cdot hour^{-1}$. Half of these wells possess yields of $<2\,m^3 \cdot hour^{-1}$ whereas 15 wells had yields exceeding $5\,m^3 \cdot hour^{-1}$. Low yielding boreholes are predominantly located in upland areas where the regolith is thin whereas high yielding boreholes are most commonly located in low-lying areas underlain by a comparatively thicker regolith. Across the basin, low-intensity (handpump) abstraction of groundwater ($<0.7\,m^3 \cdot hour^{-1}$ per borehole) has taken place for decades from boreholes installed primarily into the fractured bedrock aquifer to supply potable water to the overwhelmingly rural population. Consequently, the predominance of higher yields observed in boreholes in low catena positions likely reflects one or both of enhanced bedrock transmissivities associated with greater fracturing and enhanced groundwater storage, sustaining higher yields, where the regolith is thicker. More recently, intensive

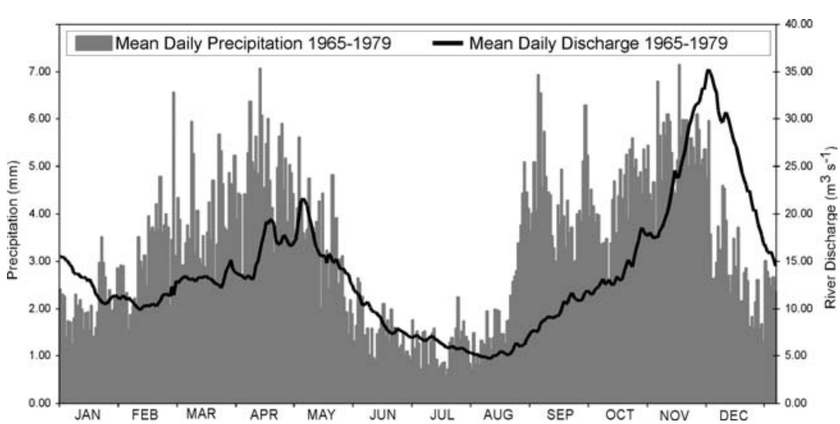

Figure 2.2. Mean daily rainfall (20 stations) and river discharge in the River Mitano basin from 1965 to 1980 (Mileham 2008).

groundwater abstraction from the saprock-saprolite aquifer system by motorised pumps ($>3.6\,m^3 \cdot hour^{-1}$ per borehole) has been conducted to supply the rapidly growing town of Rukungiri located in the north-central part of the basin.

2.2 RESULTS AND DISCUSSION

2.2.1 Impacts of intensive groundwater abstraction

Intensive groundwater abstraction in Sub-Saharan Africa (SSA) is primarily conducted for town and city water supplies as either a primary (e.g. Dodoma, Tanzania; Lusaka, Zambia) or supplementary (e.g. Nairobi, Kenya; Dar es Salaam, Tanzania) source of potable water. Smaller towns throughout SSA can be entirely dependent on groundwater as a source of potable water because such systems do not require the expense and expertise of sophisticated water treatment. For many towns, groundwater is their only source of water for some or all of the year. Intensive groundwater abstraction was promoted in many parts of SSA during the 1990s under a number of schemes including the Small Towns Water and Sanitation Project funded among others by the World Bank, DANIDA, the European Union, and African Development Bank. Intensive groundwater abstraction for irrigation in SSA is currently minimal and restricted to few locations (e.g. Kabwe, Zambia). Regionally, less than 5% of the arable land in SSA is under irrigation from either surface water or groundwater withdrawals (Giordano 2006). Substantial increases in groundwater withdrawals for irrigation are, however, proposed (World Bank 2007) to improve food production and the resilience of agricultural systems in SSA to climate variability and change.

The town of Rukungiri in the River Mitano Basin with an estimated population of 18,600 in 2006 relies exclusively upon groundwater for its piped water supply that is based on two high yielding boreholes. Motorised abstraction from one borehole commenced in 1998 but substantially increased after February 2003 to between 150 and $200\,m^3 \cdot day^{-1}$ using both boreholes following a sharp rise in demand (MWLE 2006). This piped water supply is unable to meet demand and currently supplemented by 14 hand-pumped boreholes and 47 springs in the town in addition to another motorised borehole privately operated by a local hospital. The percentage of the population with access to safe water in the town is 71%. Of this, 56% are supplied by the piped water supply system whereas 15% are supplied by the point water sources (MWE 2006).

Both production boreholes are located in a wellfield near the base of a valley and installed into a thick (60 to 70 m) sequence of not only *in situ* weathered rocks but also colluvial and possibly alluvial fine, medium and coarse-grained sands. Surface geophysical investigations employing using electrical resistivity indicate that the wellfield is bounded geologically by dense, relatively unfractured bedrock (Tindimugaya 2008). The discontinuous nature of aquifers in the unconsolidated regolith is expected on stripped surfaces where the rejuvenation of drainage promotes colluvial and alluvial erosion (Taylor and Howard 2000). In Rukungiri Town and Mitano Basin, erosion to a new base level for drainage was triggered by downfaulting of the western arm of the East African Rift and creation of Lake Edward during the Pleistocene (Fig. 2.1b). On low-relief surfaces where the regolith is regionally extensive, it remains unclear whether aquifers within the regolith are regional or effectively discontinuous due to substantial variability in the regolith's lithology and hydraulic conductivity.

Combined rainfall and groundwater-level monitoring around the two production wells in Rukungiri Town was initiated after the commissioning of the town's piped water supply system (Fig. 2.3). Monitoring records for the production borehole (Ruk 5) that was unpumped show initially the response of the aquifer from September 2001 to January 2003 to estimated rainfall-fed recharge (Mileham et al. 2008) and subsequently intensive abstraction from February 2003 to August 2005. Small positive deflections in the groundwater-level record reveal episodic recharge events that are restricted to heavy rainfall events ($>10\,\mathrm{mm \cdot d^{-1}}$) during monsoons. This pattern has been observed elsewhere in Uganda (Taylor and Howard 1996; Owor et al., 2009) and is discussed further in the next section.

A sharp drop and sustained decline in the observed groundwater level from 10 m below ground level (mbgl) in February 2003 to 25 mbgl by August 2004 (Fig. 2.3) occur in response to groundwater abstraction in the order of $120\,\mathrm{m^3 \cdot day^{-1}}$. This substantial ($\sim$15 m) and sustained decline in observed groundwater level suggests that abstraction has drawn from long-term storage. Strong positive deflections in the hydrograph after February 2003 not only correspond well with estimated recharge events but suggest further that the pumping borehole captures more recharge than under previous, non-pumping conditions. The extent to which positive deflections in groundwater

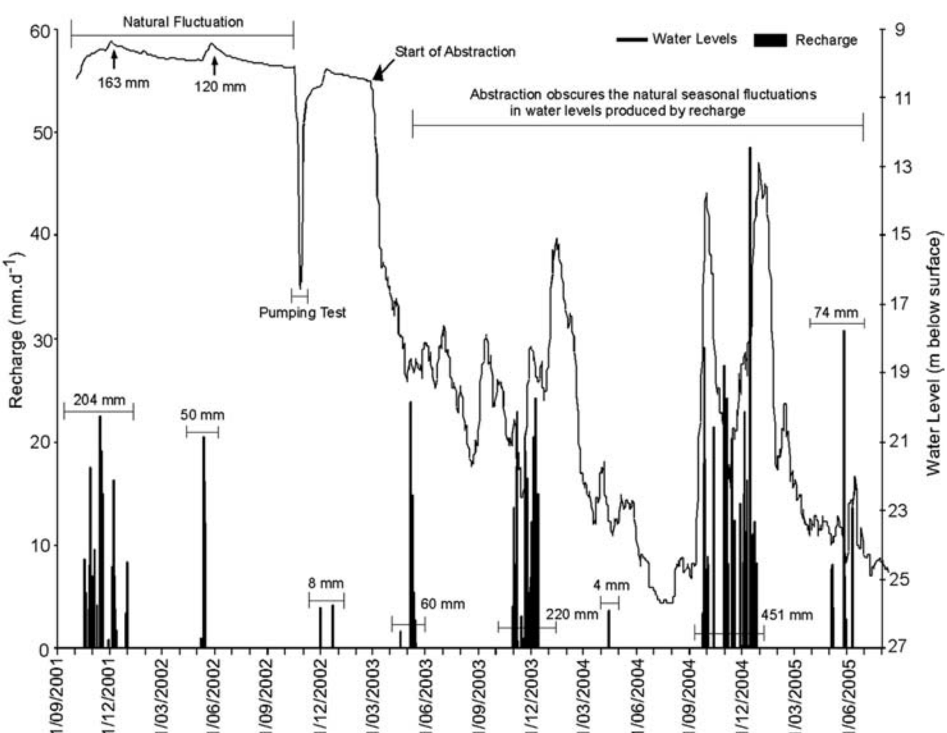

Figure 2.3. Groundwater-level hydrograph for production borehole, Ruk 5 (Tindimugaya 2008) and estimated recharge (Mileham 2008) in Rukungiri Town from September 2001 to August 2005.

levels arise from variability in daily abstraction is, however, unclear. Continued pumping has led to shorter but more frequent periods of pumping as maximum pumping depths (determined by the depth of the submersible pump and borehole itself) are realised more quickly. A third production borehole, approximately 2 km away, has recently been commissioned to supplement the water from the two existing boreholes but the town's current water demand still remains unmet. Monitoring of groundwater levels in Rukungiri Town highlights how the localised nature of aquifers in deeply weathered crystalline rock environments constrains the long-term sustainability of intensive abstraction using submersible pumps (i.e. rates exceeding $>1\ \mathrm{L \cdot s^{-1}}$ per borehole).

2.2.2 Impact of climate change on groundwater recharge

An important, generic impact of human-induced warming on the global hydrological system is an increased frequency of very heavy rainfall events, specifically those in the uppermost quantiles of the rainfall distribution (Allen and Ingram 2002; Trenberth et al. 2003; Pall et al. 2007). The shift to more intensive rainfall is explained by the fact that water-holding capacity of the atmosphere increases according to the Clausius–Clapeyron relation ($\sim$6.5% $\mathrm{K^{-1}}$ rise in air temperature) and the observation that heaviest rainfall events tend to deplete air of all of its available moisture. Recent analyses (Allan and Soden 2008; Min et al. 2011) verify this conceptual model and suggest further that the amplification of very heavy rainfall events under a warmer atmosphere is greater than that currently projected by General Circulation Models (GCMs). As warmer air temperatures in the humid tropics lead to larger absolute rises in the moisture content of the atmosphere, it is here where increased rainfall intensities are expected to be especially pronounced.

In the humid tropics, effective precipitation (i.e. that which contributes to groundwater recharge and runoff) depends upon heavy rainfall events when the rate of incoming rainfall temporarily exceeds high rates ($>4\ \mathrm{mm \cdot day^{-1}}$) of potential evapotranspiration (PET) and soil moisture deficits that have accrued from this flux. In tropical Africa, there is a growing body of evidence from stable isotope tracers (Vogel and Urk 1975; Taylor and Howard 1999a), soil-moisture balance models (Taylor and Howard 1996; Eilers et al. 2007; Mileham et al. 2008) and borehole hydrographs (Owor et al. 2009) that demonstrates the importance of heavy rainfall events ($>10\ \mathrm{mm\ day^{-1}}$) in determining the magnitude and timing of direct, rainfall-fed recharge. Using a dataset of coincidental, daily observations of rainfall and groundwater levels remote from abstraction at 4 stations in the Upper Nile Basin of Uganda over the period 1999 to 2008, Owor et al. (2009) show that the magnitude of observed recharge events is better related to the sum of heavy rainfalls that exceed a threshold of $10\ \mathrm{mm \cdot day^{-1}}$ compared to that of all daily rainfall events. Consequently, a shift toward more frequent heavy rainfall events under an anthropogenically warmed climate should promote rather than restrict groundwater recharge in similar environments of the tropics.

Substantial (70%) declines in groundwater recharge have been projected in northeast Brazil and southwest Africa in association with higher air temperatures and lower rainfall (Döll and Florke 2005, cited in IPCC Fourth Assessment Report) yet these projections failed to consider changes in the distribution of projected daily precipitation (Kundzewicz et al. 2008). Indeed, this oversight is commonly perpetuated through the use of "delta factors" to simulate climate change impacts on basin hydrology (e.g. Tate