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Robert Maliva

Climate Change and Groundwater: Planning and Adaptations for a Changing and Uncertain Future

WSP Methods in Water Resources Evaluation Series No. 6

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Robert Maliva
WSP and Florida Gulf Coast University
Fort Myers, FL, USA

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Preface

Fresh groundwater is a vital resource for global potable, irrigation, and industrial water supply. Groundwater has the great advantages as a water supply of often enormous volumes in storage, high-quality (and thus low treatment costs), and widespread and ready access across groundwater basins, which allows for convenient decentralized use. The advantages of groundwater use have led to overexploitation in many areas of the world as manifested by declining groundwater levels and associated adverse impacts, such as salinization of aquifers, land subsidence, declining spring flows, and drying of wetlands. Global groundwater use, and thus aquifer depletion, has increased over time due to population growth, economic development, climate variation, and other factors.

Global climate change will result in increased temperatures, which will likely increase water demands, and modifications of global precipitation rates and patterns, and thus aquifer recharge. There is still considerable uncertainty as to local directions and magnitudes of changes in precipitation. Some areas, such as southwestern North America and Mediterranean region, are anticipated to experience drier conditions, and droughts may become more frequent and intense. Groundwater will increasingly be needed to perform a stabilization role in mitigating fluctuations in the supply of surface waters, serving as a buffer against droughts.

Climate change has become a frequent subject in the mass media, and the academic literature on the subject is now enormous with many thousands of papers and numerous dedicated journals, books, organizations, conferences, conference sections, and Internet sites. The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations to provide “policymakers with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation options.” Virtually, every aspect of climate change has been the subject of multiple technical papers or dissertations. The challenge is not that the climate change literature is incomplete but rather that it is overwhelming to people outside of the climate change research community.

A number of workers have observed with respect to climate change and water that a chasm exists between the climate change research community and the decision-making community. Decision makers are water users and the staff of water utilities and regional water suppliers who are actually responsible for developing water supplies to meet their own needs and those of their customers. Researchers are frustrated that the result of their climate change modeling and projections are not adequately being considered in water supply planning and implementation. Decision makers often find the output of the climate change research community to not be directly actionable, that is, capable of being acted upon in their water supply planning processes. High degrees of uncertainty in climate change projections limit their usefulness in the traditional water supply planning process.

The "Methods in Water Resources Evaluation" series approaches hydrogeology and water resources evaluation and development from an applied perspective. Key considerations are what is technically and economically practicable for those responsible for developing and managing water resources, which may not necessarily be the current technical state of the art in academia. Water supply investigations have finite budgets and time constraints. *Climate Change and Groundwater: Planning and Adaptations for a Changing and Uncertain Futur*e attempts to bridge the chasm between the climate change research and decision-making communities with respect to the impacts of climate change on groundwater. This book is a review and numerous references are provided to key papers and data sources that can provide additional information and further guidance on climate change adaptation with respect to groundwater.

An overview is provided of the climate change modeling process and avenues for decision makers to access and efficiently use the results of the modeling. A summary is also provided of the actual decision-making processes in the water field. For climate change research to have impact, it needs to reach the actual people who make water supply decisions in a form that they can use. Issues explored are who actually makes water supply decisions, how are those decisions made, and what is the water supply planning horizon. Despite calls for climate change adaptation decisions to be broadly based with contributions from numerous stakeholders within society, water supply planning is still largely siloed to a small number of technical experts.

Climate change will impact groundwater through changes in water demands, impacts to groundwater recharge (and thus the sustainable supply of water), and through sea level rise and its impacts on the salinity of coastal aquifers and groundwater levels. Rising groundwater levels induced by sea level rise and increases in precipitation can cause flooding of low-lying areas and interfere with the operation of or damage underground infrastructure. The impacts of climate change on water resources (and society in general) are insidious in that they tend to occur so slowly as to not be noticeable by the casual observer on a year-to-year basis, which leads to complacency. However, progressively increasingly impacts from accelerating climate change may eventually profoundly impact vulnerable individuals, communities, cities, and countries.

Although climate change will impact groundwater resources in multiple manners, the impacts of population growth (and associated increases in water demands for domestic use and food supply) and economic development will tend to have a much greater impact on groundwater resources. Climate change may exacerbate an already deteriorating situation in arid and semiarid regions. It is also important to recognize that some areas may experience net benefits from climate change. Vast disparities exist between countries and regions in their ability to adapt to climate change (i.e., their adaptive capacity).

Climate change vulnerability or risk assessments involve systematic consideration of how various elements of water supply systems and other infrastructure could be impacted under different climate change scenarios, the probability of the damaging scenarios, when in the future the damage might occur, and the magnitude of the harm. Once risks are assessed, the next step is evaluation of adaptation options to ameliorate the risks. Most adaptation options for climate change are essentially the same as those for water scarcity in general. In areas experiencing drier conditions or growing water demands that exceed their sustainable supplies of groundwater and local surface water, water supplies and demands will have to be brought into balance by some combination of demand reduction, reallocation of water to higher value uses (i.e., from agricultural to domestic and commercial/industrial uses), development of alternative water sources (e.g., desalination and wastewater reuse), and optimization of the use of existing resources through conjugate use and managed aquifer recharge. The impacts of climate change on groundwater will be gradual. Rather than requiring immediate adaptive actions, climate change is an additional factor that needs to be incorporated (i.e., mainstreamed) into existing water supply and land-use planning processes.

Fort Myers, USA Robert Maliva

Contents

About the Author

Dr. Robert Maliva has been a consulting hydrogeologist since 1992 and is currently a Principal Hydrogeologist with WSP USA Inc. and a Courtesy Faculty Member at the U.A. Whitaker College of Engineering, Florida Gulf Coast University. He is currently based in Fort Myers, Florida. Dr. Maliva specializes in groundwater resources development including alternative water supply, managed aquifer recharge, and desalination projects.

Robert Maliva completed his Ph.D. in geology at Harvard University in 1988. He also has a Masters degree from Indiana University (Bloomington) and a BA in geological sciences and biological sciences from the State University of New York at Binghamton. Upon completion of his doctorate degree, Dr. Maliva has held research positions in the Department of Earth Sciences at the University of Cambridge, England, and the Rosenstiel School of Marine and Atmospheric Science of the University of Miami, Florida. He grew up in New York City and attended Stuyvesant High School in Manhattan.

Dr. Maliva has also managed or performed numerous other types of water resources and hydrologic investigations including contamination assessments, environmental site assessments, water supply investigations, wellfield designs, and alternative water supply investigations. He has maintained his research interests and completed studies on such diverse topics Precambrian silica diagenesis, aquifer heterogeneity, precipitates in landfill leachate systems, carbonate diagenesis, and various aspects of the geology of Florida. Dr. Maliva gives frequent technical presentations and has numerous peer-reviewed papers and conference proceedings publications on ASR and injection well and water supply issues, hydrogeology, and carbonate geology and diagenesis. He authored or coauthored the books, *Aquifer Storage and Recovery and Managed Aquifer Recharge Using Wells, Arid Lands Water Evaluation and Management, Aquifer Characterization, and Anthropogenic Aquifer Recharge.*

Chapter 1
Introduction to Climate Change and Groundwater

1.1 Introduction

There is now little doubt in the scientific community that the Earth's climate is changing at an accelerating rate and that rising global temperatures are due largely to increasing atmospheric concentrations of greenhouse gases (GHGs). Climate change is already impacting ecosystems and will have growing disruptive impacts on human health and many important sectors of societies, including housing, healthcare, transportation, energy, food, basic materials, and water supplies. Climate change has become the subject of overwhelming attention in academia with an enormous volume of papers, dissertations, and books published, and dedicated journals, website sites, and conference and conference sessions on all aspects of the subject. Despite all the attention that climate change is receiving in academia and the popular press, there is widespread frustration that not enough is being done to mitigate and adapt to climate change.

Climate change mitigation, which is primarily the reduction of GHG emissions, ultimately requires international agreement and national government-level commitments and actions. Adaptation actions, on the contrary, are largely undertaken by the impacted parties, although higher level (i.e., international, national, or state) technical and financial support may be required. Activities taken in response to anthropogenic climate change contribute to the sustainable development goal of making societies more resilient to changes in general (Pielke et al. 2007). "Virtually every climate impact projected to result from increasing greenhouse-gas concentrations—from rising storm damage to declining biodiversity—already exists as a major concern. As long as adaptation is discussed in terms of its marginal effects on anthropogenic climate change, its real importance for society is obscured" (Pielke et al. 2007, p. 598).

Changes in temperature and precipitation will potentially affect local water demands and supplies, with the degrees of impacts depending on the direction, magnitude, and type of climate change and local circumstances, including existing

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climate conditions, the amount and types of water use (e.g., domestic, agricultural, and industrial), and the water sources exploited. The impacts of climate change in many areas will be superimposed on increasing water scarcity associated with population growth and economic development. Groundwater was estimated to globally provide 50% of domestic water supplies, 40% of self-provided industrial supplies, and 20% of irrigation supplies (Zekster and Everett 2004). More recent estimates by Siebert et al. (2010) indicate that the total global consumptive use of groundwater for irrigation is about 545 km^3/yr, which corresponds to 43% of the total consumptive irrigation water use of 1277 km^3/yr. The countries with the largest areas equipped for irrigation with groundwater, in absolute terms, are India (39 million ha), China (19 million ha) and the USA (17 million ha; Siebert et al. 2010). Irrigation is critical for meeting global food demands but expanding groundwater use for irrigation (both in absolute terms and as a percentage of total irrigation) is resulting in increasing aquifer overdrafts and declining aquifer water levels (Seibert et al. 2010).

Groundwater resources will be under even greater pressure if declines in surface water availability are compensated for by increased groundwater use. A number of studies reviewed the impacts of climate change on groundwater (e.g., Arnell 1999; Vörösmarty et al. 2000; Ranjan et al. 2006; Bates et al. 2008; Dragoni and Sukhija 2008; Kundzewicz et al. 2008; Earman and Dettinger 2011; Green et al. 2011; Taylor et al. 2013; Green 2016). Groundwater will be needed to play a key role in the adaptation of water supplies to climate change by serving as a buffer against variations in surface water supplies (Alley 2001; Green 2016). A basic conjugative use strategy is that surface water is used when available to meet immediate demands and to recharge aquifers. Groundwater is reserved for times when surface water supplies are inadequate to meet demands.

The option of using groundwater as a long-term buffer against surface-water shortages requires that groundwater use be sustainable. Groundwater will likely not be able to ease freshwater stress in those areas where climate change is projected to decrease groundwater recharge or where groundwater use is unsustainable under current climate conditions (Kundzewicz and Döll 2009). The unfortunate reality is that most of the major aquifers in the world's arid and semiarid zones are already experiencing rapid rates of groundwater depletion (Döll et al. 2014; Famiglietti 2014).

A major impediment to climate change adaptation, in general, is poor communication between the climate change research community and decision makers. With respect to water supply, decision makers are normally individual water users (in the case of self-supply) and the technical staff and management of local water utilities and regional water suppliers. Regional water suppliers provide wholesale raw or treated water to municipal water utilities and other large customers. Examples, of large regional water suppliers in the United States are Tampa Bay Water, Peace River Manasota Regional Water Supply Authority (Florida), Southern Nevada Water Authority, Tarrant Regional Water District (Texas), and Metropolitan Water District of Southern California. In the author's home in Southwest Florida, for example, water supply decisions are made by a local public water utility (Lee County Utilities), whose choices of supply (e.g., amount of fresh groundwater that can be pumped) are constrained by a regional governmental water management agency (South Florida Water Management District). Fresh groundwater is the preferred (least expensive) source of water, but its permitted use is capped because of environmental concerns, particularly impacts to wetlands.

The Intergovernmental Panel on Climate Change (IPCC) observed that

> Previous assessment methods and policy advice have been framed by the assumption that better science will lead to better decisions. Extensive evidence from the decision sciences shows that while good scientific and technical information is necessary, it is not sufficient, and decisions require context-appropriate decision-support processes and tools. (Jones et al. 2014, p. 198)

Much of the academic climate change research literature is written for other members of the research community and published in obscure (to the lay public) places. Decision makers inherently need “actionable” information that they can use in their water supply planning activities.

Adger et al. (2005, p. 79) made the key observations that “Adapting to climate change involves cascading decisions across a landscape made up of agents from individuals, firms and civil society, to public bodies and governments at local, regional and national scales, and international agencies” and that “a broad distinction can be drawn between action that often involves creating policies or regulations to build adaptive capacity and action that implements operational adaptation decisions.” With respect to water supply planning, and thus climate change adaptation decision making, scientific and technical information on climate change needs to flow to water users and suppliers in a form that is understandable and usable to them, which includes projections of the probability and likely timing and magnitude of changes.

The objective of this book is to explore the impacts of climate change on groundwater, and adaptation and resiliency enhancement options from an applied perspective. Overviews are provided of historical anthropogenic (human-caused) climate change, climate modeling, the impacts of climate change on groundwater, vulnerability assessments, adaptation options, and the data and methods available to assess potential local impacts. A key focus is on available data sources and methodologies that can provide required information or guidance and are within the technical and financial resources of water users, utilities, and other water suppliers.

1.2 Climate Change and Groundwater

Sunlight (relatively shortwave energy) passes through the Earth’s atmosphere and is reradiated back into space as longer wavelength infrared (thermal) energy (Fig. 1.1). GHGs are chemical compounds present in the Earth’s atmosphere that allow sunlight to pass through but allow less heat to be reradiated back into space, causing a heating of the lower atmosphere. GHGs include compounds that are naturally present in the atmosphere (e.g., carbon dioxide, methane, water vapor, and

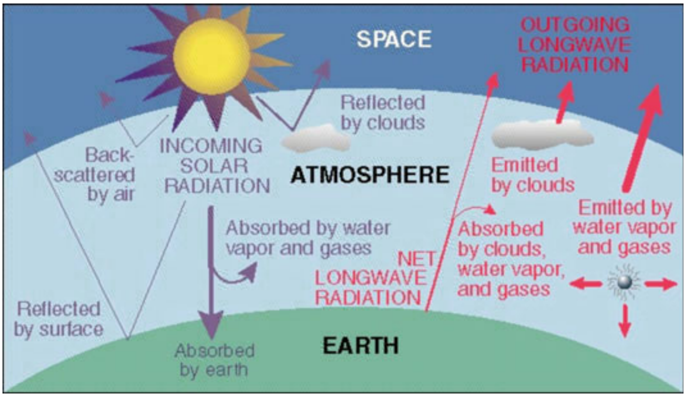

Fig. 1.1 Diagram of the greenhouse effect. Incoming solar radiation in absorbed by the Earth's surface and atmosphere and converted to long-wave thermal radiation, which is mostly radiated back into space. Increasing GHG concentrations result in the retention of more heat in the lower atmosphere. *Source* Markewich et al. (1997)

nitrous oxide) and synthetic compounds (e.g., chlorofluorocarbons, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride; NOAA n.d.). Rising GHG concentrations increase the amount of thermal energy trapped in the lower atmosphere. The contributions of the various GHGs to global warming depend on their concentration, absorption strength, atmospheric residence time, and molecular mass, and the time period over which climate effects are of concern (Loaiciga et al. 1996).

The greenhouse effect resulting from increasing atmospheric concentrations of GHGs is causing a progressive rise in the temperature of the Earth's surface and lower atmosphere. Increased atmospheric temperatures are causing sea levels to rise mainly by the thermal expansion of the oceans and the melting of glaciers and polar ice caps. Increasing temperatures result in greater evaporation rates and, in turn, greater precipitation rates, which has been referred to as an intensification or acceleration of the global hydrologic cycle (Loaiciga et al. 1996).

An important distinction, often not understood by some of the general public, is between weather and climate. Spells of cold weather have been cited by climate change skeptics as evidence against global warming. Weather is short-term changes in the state of the atmosphere (temperature, humidity, cloudiness, precipitation) in a region, whereas climate is long-term average conditions. Global temperature projections indicate increasing variation around a progressively rising mean. The impacts of climate change are also projected to have considerable geographic variability. Whereas mean annual temperature is expected to increase essentially everywhere (but to varying degrees), some regions will experience either lesser or greater annual precipitation. The timing, form, and intensity of precipitation will also change with expected lesser snowfall and a greater intensity of rainfall events. Changes in temperature and precipitation will impact both the supply of and demand for water.

Climate has considerable natural variation on different time scales. Regional temperature and precipitation patterns (droughts and wet periods) are impacted by natural oceanic cyclicity, particularly the El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO; McCabe et al. 2004; Hu and Huang 2009; Kuss and Gurdak 2014; Abiy et al. 2019). In evaluations of current climate changes in response to historical increases in GHG concentrations, an important consideration is the signal-to-noise ratio (Loaiciga et al. 1996). Over short periods of time, the climate change signal may be significantly smaller than the natural variability. However, in recent years unusually warm periods have become more frequent than can be explained as random events that are part of the natural climate variation. Hansen et al. (2012) described the tendency toward more common extreme events as the "climate dice" having become more and more "loaded" over the past 30 years, coincident with rapid global warming.

Groundwater is a critical source of water for both potable and irrigation uses and, to a lesser extent, industrial uses, and supports groundwater dependent ecosystems. Groundwater is generally less sensitive to short-term climatic variations than surface water supplies because of the very large volumes of water in underground storage in aquifers. Groundwater use is already at or above sustainable levels in much of the drier parts of the world and demands on groundwater are increasing due to population growth and economic development. In areas that are experiencing drier conditions due to climate change, there will likely be increasing pressure on groundwater resources to compensate for shortages in surface water supplies and decreasing soil moisture.

The literature on climate change focuses on two plausible strategic responses: mitigation and the related concepts of adaptation, coping, and resilience. Mitigation involves primarily policies to reduce greenhouse gas (GHG) emissions and thus decrease the rate and magnitude of climate changes. Adaptation in human systems was defined by the IPCC (2012) as "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities." Coping is defined as the "use of available skills, resources, and opportunities to address, manage, and overcome adverse conditions, with the aim of achieving basic functioning in the short to medium term" (IPCC 2012). Resilience is defined as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions" (IPCC 2012).

It is clearly desirable to mitigate against climate change. However, even with the implementation of drastic mitigation actions, climate change will continue to occur because of historical GHG emissions. Therefore, humans will be forced out of necessity to adapt to climate change with the preferred option being to increase the resilience of systems to accommodate a wide range of possible future climates. Human societies have varying abilities to adapt to local climate change, which is referred to as their adaptive capacity. Wealthier countries have the technical and financial resources to increase their resilience to climate change, whereas poorer developing countries have more limited options to cope with and adapt to climate change.

Adaptation to climate change continues to be the subject of considerable academic research, but for that research to be useful, the gap between climate change researchers and decision makers who need to use the results of the research must be bridged (Ferguson et al. 2014; Hewitt et al. 2017). With respect to groundwater, the term "decision maker" broadly includes all managerial, technical, and regulatory staff who are actively involved in the water supply planning process. Evaluating the potential impacts of climate change on local groundwater resources and identifying and applying options to optimize the management of groundwater under changing climate conditions is squarely in the realm of applied hydrogeology. The scientific community is needed to provide decision makers with information that is of practical use in the water supply planning process (i.e., is actionable).

Although this volume is focused on groundwater, effective management of groundwater resources requires a holistic approach in which other water resources are considered along with factors controlling water demand, and water governance rules and processes. The basic information requirements for adaptation of groundwater use to climate change and developing more resilient water supplies start with an understanding of the potential local direction and rates of changes of climate variables (particularly temperature, precipitation, and local seal level) and how local groundwater resources will respond to changes in those variables.

The initial step in adaptation planning is an evaluation of how climate change might locally impact groundwater quantity and quality, which, in additional to evaluating the direct effects of changes in temperature, precipitation, and sea level, also involves consideration of potential changes in the water demands of anthropogenic and natural systems, and potential changes in land uses and land cover. Climate change vulnerability assessments commence with a qualitative screening of potential risks from climate change. Qualitative screenings are followed by quantitative assessments that consider the probability, potential magnitude, and timing of identified risks. Quantitative assessments of impacts to groundwater systems often involve some type of numerical modeling. Vulnerability assessments, by their nature, involve consideration of adverse changes, but it is important to also recognize that climate change can also provide some benefits. For example, increased precipitation may locally reduce irrigation demands and increase aquifer recharge.

Adaptation planning is an exercise in management under uncertainty because there is a broad range of possible future climate scenarios. Given identified vulnerabilities, various actions are identified that can be employed to improve the resilience of groundwater resources, vulnerable infrastructure, and water supplies in general. It is now widely appreciated in the adaptation literature that robust ("no regrets" or "win-win") interventions that would provide benefits under current and a wide range of future climate conditions are preferred (Hallegatte 2009; Heltberg et al. 2009). Adaptation options should be avoided that would perform well under some future climate scenarios but may be maladapted to other plausible scenarios that might actually come to pass.

Where groundwater levels are expected to decline as a result of decreased recharge, managed aquifer recharge (MAR) technologies are available to increase groundwater recharge. Managed aquifer recharge (MAR), which is defined as the "purposeful recharge of water to aquifers for subsequent recovery or environmental benefit" (Dillon 2009), includes a broad suite of technologies to store and treat water underground.

The implementation of climate change adaptation actions can be either prompted or constrained by local groundwater governance regimes. Governmental agencies that regulate water use through restrictions on groundwater pumping and surface water withdrawals may create incentives for investments in MAR and alternative water supply systems (e.g., brackish groundwater desalination). Research performed or financially supported by governmental agencies provides the scientific foundation for the decision-making process. Governmental financial assistance may be required to support local implementation of measures to increase resilience. International support will needed for poorer developing countries that have neither the technical nor financial resources to adapt to climate changes for which they have had a minimal contribution. Conversely, environmental protection rules and policies for the quality of recharged water, and thus pretreatment requirements, can make some options, such as MAR using reclaimed wastewater, economically unviable.

The water planning horizons for water users and regulatory agencies influence adaptation responses. If expected local climate changes and sea level rise are small over planning horizons, then water users and suppliers may not place a high priority now on implementing adaptation actions against climate change.

1.3 Climate Change Modeling

The foundation of climate change predictions is general circulation models (GCMs), which are also referred to as global climate models. GCMs are three-dimensional models that include the entire planet. Coupled atmosphere-ocean general circulation models (AOGCMs) simulate all major processes that impact climate, including sea ice and evapotranspiration over land. Even more complex and comprehensive are earth system models (ESMs) that include representations of various biogeochemical cycles.

A key input to GCMs is the future atmospheric concentrations of GHGs (and other substances impacting atmospheric warming, e.g., aerosols). Future GHG concentrations are inherently unknowable as they depend upon future economic growth, technological developments, energy supply choices, and mitigation actions. To allow for direct comparison of the results from different GCMs, model runs have been performed using the same set of future GHG concentration scenarios. The IPCC for its Fifth Assessment Report (AR5) in 2014 adopted four Representative Concentration Pathways (RCPs) that represent a range of long-term concentration levels and trajectories taken over time to reach them. The results from an ensemble of runs of multiple GCMs using the RCPs, and earlier SRES (Special Report on Emissions Report) scenarios, provide a broad range of plausible future climate conditions. The Coupled Model Intercomparison Project Phase 5 (CMIP5) is a collaborative effort involving more than 20 climate modeling groups from around the world. A standard set of model simulations were run (using the RCPs) in order to evaluate how realistic the models are in simulating the recent past and to understand some of the factors responsible for differences in model projections (PCMDI n.d.). The IPCC AR5 relied heavily on the CMIP5 results, which have also been used in many other climate change studies.

The typical horizontal resolution (horizontal grid spacing) of current AOGCMs and ESMs is approximately 1°–2° for the atmospheric component and around 1° for the ocean and land (Flato et al. 2013). GCMs are thus suitable for simulating only large spatial-scale climate changes rather than more local changes that are pertinent for water supply planning. For more accurate local projections of climate change, GCM data need to be downscaled, which is most commonly performed using dynamic and statistical methods. Dynamic downscaling involves the creation of a finer-grid numerical model (i.e., a regional climate model; RCM) that is forced by (obtains boundary conditions from) a GCM. Statistical downscaling involves the development of fine-scale maps of climate change through the statistical relationships between local climate variables (e.g., temperature and precipitation) and the large-scale outputs of GCMs (Wilby et al. 2004).

Climate modeling is a very complex and specialized discipline with only a small number of research groups capable of developing GCMs and RCMs. The CMIP5 simulations results have been archived and are available to external users. The CMIP5 results are summarized in the IPCC AR5 (IPCC 2013) and are accessible using some interactive viewer programs such as the U.S. Geological Survey CMIP5 Global Climate Change Viewer (Alder et al. 2013; USGS n.d.) The Climate Wizard tool accesses some of the earlier CMIP4 modeling results that supported the IPCC Fourth Assessment Report (AR4; CGIAR n.d.)

1.4 Projected Global Climate Changes

Numerical modeling, whether it be of climate, groundwater, or surface water, is not an exact science and there is inherently considerable uncertainty in the results. Climate modeling predictions are subject to a "cascade of uncertainties," which flows from uncertainties in emissions scenarios (i.e., future GHG concentrations), to uncertainties in the GCM simulations of the climatic response to a given GHG scenario, and then to the downscaling of the GCM data to the regional and local scales, and subsequent hydrologic modeling (e.g., Foley 2010; Mitchell and Hulme 1999; Maslin 2013; Vaghefi et al. 2019; Falloon et al. 2014). The uncertainties in each step are compounded to result in large uncertainties in final projections. Nevertheless, both historical trends and a consensus of the modeling results unequivocally indicate that the Earth's climate has been warming over the past century and will continue to do so at an accelerating rate into the future.

Depending on which RCP most closely comes to pass, the increase in global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is projected to likely range from 0.3 to 1.7 °C under the lowest emissions RCP2.6 to between 2.6 and 4.8 °C under the highest emission RCP8.5 (IPCC 2014). Land areas will warm more than the oceans and the greatest temperature increases will occur at high latitudes in the northern hemisphere (IPCC 2014). In additional to an increase in mean temperatures, extreme high temperature events (heat waves) are projected to become more common.

Changes in precipitation will not be uniform. As a broad generalization, many mid-latitude and subtropical dry regions will likely experience decreasing precipitation, while many mid-latitude wet regions will likely become wetter (IPCC 2014). High latitude areas and the equatorial Pacific are likely to experience an increase in annual mean precipitation under the RCP8.5 scenario (IPCC 2014). Extreme precipitation events and droughts are generally expected to become more common.

Global warming is expected to alter the hydrologic cycle in snowmelt-dominated regions by decreasing the amount of precipitation that falls in mountainous areas as snow, and thus the thickness of the winter snowpack, and cause an earlier melting of the snowpack. Changes in hydrologic conditions are expected to increase flood risk in the winter and early spring and decrease water availability in the summer. The changes in hydrologic conditions in snowmelt-dominated regions may impact groundwater recharge in mountainous areas although the direction and magnitude of changes in recharge are generally uncertain (Green 2016).

Modeling results indicate that sea level will continue its historical rise and that the rate of rise will very likely increase as the atmosphere and oceans warm. Local sea level rise may significantly vary from the global mean rate depending on such factors as changes in land elevation (e.g., from subsidence and isostatic rebound), winds, and ocean circulation. The latest IPCC (2019) projections are that the global mean sea level (GMSL) rise with respect to 1986–2005 under the low emissions RCP2.6 scenario will be 0.39 m (0.26–0.53 m, *likely range*) for the period 2081–2100, and 0.43 m (0.29–0.59 m, *likely range*) in 2100. For the higher emissions RCP8.5 scenario, the corresponding projected GMSL rise is 0.71 m (0.51–0.92 m, *likely range*) for 2081–2100 and 0.84 m (0.61–1.10 m, *likely range*) in 2100 (IPCC 2019). The IPCC (2019) also projected that there is a high confidence that extreme sea level events that are historically rare (once per century in the recent past) will occur frequently (at least once per year) at many locations by 2050 in all RCP scenarios, especially in tropical regions. The wild card with respect to sea level rise is the rate of melting of the polar ice caps. If the rate of melting is faster than expected, then sea level rise will be substantially more rapid than historical and projected rates.

1.5 Climate Change and Groundwater Recharge and Use

Climate change will impact groundwater resources mainly through changes in the amount of recharge and the demand for groundwater, and through impacts to water quality. Recharge is broadly defined as the flow of water from surface water bodies and land surfaces to underlying aquifers. Changes in annual average precipitation impact the amount of water that is available for recharge. However, the relationship between precipitation and recharge is not linear. Recharge rates also depend on the intensity and duration of precipitation events, its form (rain versus snow), and its seasonality and temporal distribution. Changes in land cover and land uses can impact recharge rates through changes in vegetation evapotranspiration (ET) and infiltration rates. The expected trend of precipitation occurring in more intense events, depending on local hydrological conditions, could result in either less recharge as more water runs off, or greater recharge if it allows sufficient water to accumulate to overcome soil-moisture deficits, permitting water to percolate to the water table. Green (2016) observed that the data necessary for confident prediction of recharge responses to future climate conditions (e.g., long-term continuous monitoring of recharge processes) are not available in most areas. Therefore, in many regions of the world, it is unknown whether (and how much) recharge will increase or decrease under projected future climates (Green 2016).

Locally decreasing precipitation may result in increased water demands for irrigation, which could be offset by a local abandonment of agriculture, a change to less water intensive crops or cultivars, and/or increasing water use efficiency. Rising temperatures can prompt increases in agricultural irrigation through increased ET rates and, in some areas, a longer crop growing season. The transpiration rates of some plants have been shown to decrease with increasing atmospheric carbon dioxide concentrations as the result of partial stomatal closure, which could offset the temperature effect on transpiration. Domestic water use may directly increase through greater residential lawn and landscaping irrigation and indirectly through increased water consumption associated with additional energy use for cooling. The most vulnerable regions will be areas where groundwater resources are already being exploited unsustainably and a drying climate will increase water demands and reduce supplies of fresh surface water (e.g., southwestern United States, parts of India).

Groundwater quality can be impacted through saline-water intrusion induced by sea level rise or, more importantly, excessive pumping of coastal aquifers. Changes in precipitation and infiltration rates can impact the quality of recharged water and thus shallow aquifers. Decreased precipitation rates and warmer temperatures could result in an increase in the total dissolved solids concentration of recharged water (Dragoni and Sukhija 2008; Green 2016). Increased infiltration could result in either a freshening of shallow groundwater (and thus improve its quality) or a deterioration of groundwater quality if it causes the leaching of salts that accumulated in the vadose (unsaturated) zone.

1.6 Sea Level Rise and Groundwater

Sea level rise can adversely impact the quality of groundwater through the salinization of coastal aquifers. Rising sea level will most directly impact coastal aquifers by the permanent inundation of low-lying areas, coastal erosion, and infiltration of sea water during flooding from storm and extreme tidal events. Freshwater lens aquifers on small, low-elevation islands are highly vulnerable to sea level rise.

Rising sea levels can induce lateral saltwater intrusion (i.e., the landward migration of the fresh-saline groundwater interface), but the extent of intrusion will depend on whether the impacted coastal aquifer is flux or head controlled (Werner and Simmons 2009). In a flux-controlled system, the rate of ground water discharge to the sea is persistent despite changes in sea level and, as a result, saline water intrusion tends to be limited. Rising sea levels will tend to cause the water table to rise, maintaining the seaward hydraulic gradient. Where the rise of the water table is limited by drainage, head-controlled conditions will occur, and the rate of saline-water intrusion will tend to be much greater (Werner and Simmons 2009).

A rising water table can cause local flooding of low-lying areas, which is referred to as groundwater inundation. The impacts of sea level rise on coastal and island aquifers are now typically evaluated by numerical modeling using a density-dependent solute transport modeling code (e.g., SEAWAT, Guo and Langevin 2002). Vulnerability to direct inundation and groundwater inundation can be assessed using high-resolution topographic maps (digital elevation models; DEMs) and projected local sea level and groundwater rise, and by hydrodynamic modeling.

1.7 Evaluating Climate Change Impacts on Groundwater Storage

Numerical groundwater modeling incorporating GCM projections is the state-of-the-art for evaluating the impacts of climate change on groundwater resources. The technical challenge is developing practicable workflows for extracting large-scale climate change data from GCMs, downscaling the data to a local scale relevant for groundwater recharge, simulation of the surficial hydrological processes that partition precipitation into runoff, ET, and recharge, and then developing a groundwater flow model calibrated to available historical observation data (e.g., water levels). GCM projections for the different RCPs can be used to evaluate the groundwater responses to a range of future emissions scenarios. However, the cascade of the uncertainties in each modeling step can result in large uncertainties in final projections. Uncertainties related to GCMs and RCMs are typically assessed by an ensemble approach where multiple climate models run for different RCPs are used for making semi-probabilistic projections. Published studies illustrate a wide range of approaches for simulating the impact of climate change on groundwater recharge, which vary in the technical expertise and effort (and thus time and cost) required. Irrespective of the modeling procedures employed, the results of a rigorous modeling program will at best define a "cone of uncertainty" of future groundwater conditions.

An alternative to the "top-down" approach of starting with GCM projections, is the "bottom-up" scenario-based approach that starts with consideration of various plausible hydrological changes (Brown 2011). For example, groundwater flow simulations could be run with hypothetical changes in recharge rates (e.g., 10% and 20% decreases) to evaluate their impacts. If the simulation results indicate that some specific changes in recharge rates (or other variables) could materially impact groundwater levels (or other aspects of hydrologic systems of concern, such as spring flows and water levels in groundwater dependent ecosystems), then the probability of such changes is evaluated using climate modeling results.

1.8 Adaptation Options

Adaptation options for climate change are essentially the same as those available for dealing with water scarcity in general. Changes in the local supply of water can be addressed through either management of demands or changes in the water sources utilized. Groundwater depletion can be reduced through decreasing extractions by either conservation (curtailing some water uses or increasing water use efficiency) or adopting alternative water sources (e.g., reclaimed water and desalination). Unsustainable groundwater use (and thus aquifer depletion) may alternatively be allowed to continue either in a planned or unplanned manner. Indeed, production of non-renewable (fossil) groundwater is inherently unsustainable, but it may support societal development goals if done for a limited period of time to transition to more sustainable water use.

Adaptation options include conjunctive use of groundwater and surface water, seawater and brackish groundwater desalination, and wastewater reuse. Desalination is increasingly being adopted as an alternative water source, but it is expensive and energy intensive, and thus is contrary to climate change mitigation goals (unless alternate, non-fossil fuel energy sources are used). Groundwater depletion resulting from climate change can also be addressed by MAR. A deep toolbox of MAR technologies is available, such as infiltration basins and vadose and phreatic injection wells, that can be employed to recharge aquifers using excess surface water and reclaimed water supplies.

Adaptations to saline-water intrusion associated with sea level rise include reducing near coastal pumping (i.e., relocating production wells inland) and MAR techniques to restore a seaward hydraulic gradient at the fresh-saline groundwater interface. Groundwater inundation can be addressed by drainage, or elevation or relocation of high-value infrastructure.

1.9 Water Planning and Governance

"Adaptation encompasses both national and regional strategies as well as practical measures taken at all political levels and by individuals" (Green 2016, p. 124). There are great differences in the degree of governmental involvement in water management within and between countries. In the United States and many other countries, water use is governed (regulated) on the national, state, or intrastate level. The regulatory process constrains what water users may do. Permitting systems normally endeavor to limit extractions to what are considered to be the safe yield of the source, which may consider the physical availability of water, and impacts to existing users, the environment, and the aquifer (e.g., declining of water levels and salinization of aquifers). National and state governments may perform large-scale planning, support or self-perform research, and construct or subsidize water projects. However, water supply decisions are typically made by individual water users, water utilities, and regional water suppliers, which may be either governmental agencies, not-for-profit private entities, or for-profit corporations.

Climate change adaptation planning and implementation occur in the context of existing water utility and regional water supplier organizational structures and regulatory governance. Key issues that have received relatively little attention in the climate change research literature are who actually makes water supply decisions, how are decisions made, and what are the planning time horizons. Adaptation to climate change has societal impacts and it has often been advocated in the climate change literature that input from all stakeholders and a broad suite of issues (e.g., social equity) should be considered in the decision-making process (e.g., Green 2016). However, in practice, water planning decisions tend to be largely siloed to technical experts either internal to or contracted by the organizations responsible for water supplies.

Public water utilities are typically run by directors or heads who are appointed by elected officials, such as county commissions and town and city councils. Planning is performed either directly by water utility staff or in conjunction with contracted external engineering, hydrogeology, and hydrology consultants. Regional and local water supply authorities and districts are governed by a board of directors who may either be appointed by their member governments or elected by landowners or the residents of a district. Minimum planning horizons may be regulatorily prescribed. Water supply planning in the United States tends to commonly be on 20-year (in some instances 50-year) horizons. Longer-term planning horizons are employed for expensive infrastructure projects with long operational lives.

Climate change is an insidious issue in that the impacts from year to year are not so severe or even noticeable so as to prompt immediate response. Changes in precipitation related to anthropogenic climate change over a 20-year planning period may not fall outside of the range of natural variation. The principal threat of climate change on groundwater (and water in general) supply and demand may not be gradual changes in mean precipitation rates but rather changes in the frequency and intensity of extreme events. The nightmare situation for water suppliers is droughts more severe than those in the modern climate record that cause water supplies to become exhausted. Tree ring data are being used in the western United States for climate reconstruction to identify past extreme droughts that could be a harbinger of future conditions in a drying climate (e.g., Bekker et al. 2014; Williams et al. 2020).

Groundwater governance (i.e., regulatory environment) controls the manner and extent to which water use is effectively regulated. Water governance addresses who has access to water and how water is allocated during times of shortage. Where water governance in strong, opportunities exist to control groundwater use to sustainable levels. Weak governance can lead to a "tragedy of the commons" situation resulting in over exploitation of aquifers to the ultimate harm of all users. Water use and environmental regulations limit the adaptation options that are allowed and impact the costs of their implementation. For example, water quality standards for aquifer recharge, and resulting pretreatment requirements, can make some MAR options economically unviable despite their water supply benefits. Water governance also influences the incentives for implementing some adaptation measures. To encourage MAR, the local regulatory environment should allow the owner and operator of systems to capture the benefits of their recharge and prevent third parties that are not contributing to the systems (i.e., free riders) from stealing the recharged water for their own benefit.

1.10 Climate Change Adaptation Planning Process

Climate change adaption planning starts with vulnerability assessments, which are systematic evaluations of the potential climate changes that are plausible in the area of interest and how the identified changes might impact water and related infrastructure of concern. The assessments usually incorporate the basic risk assessment process of evaluating both the probabilities of a series of adverse impacts and the potential magnitudes of the impacts (degrees of harm). Once vulnerabilities are identified, possible options are explored that could reduce or eliminate each identified risk. Adaptation planning for water supplies involves the investigation of potential responses to the impacts of climate change and how those responses can be best integrated into existing water supply systems. Water supply planning is essentially an exercise in multiple-criteria decision analysis (MCDA) in which overall strategies and specific supply options are evaluated based on the degree to which they achieve each of multiple criteria, of which reliability and cost are usually of greatest importance.

The degree of sophistication of water supply planning varies greatly between water utilities and regional suppliers. Small utilities supplied solely by groundwater may adapt to climate change by implementing conservation measures and perhaps managed aquifer recharge. The choice of practical options is limited, and the decision-making process is relatively simple. A small number of options may be identified that achieve water supply requirements, which are judged by their costs (and other relevant considerations).

Larger utilities and regional water suppliers with multiple water sources and complex supply and distribution infrastructure require more sophisticated planning tools to identify optimal solutions. The current state of the art is decision support systems (DSSs), which incorporate both hydrological simulation and various optimization algorithms. The most sophisticated DSSs also include modules that estimate the impacts of climate change on water demands and other socioeconomic factors (Serrat-Capdevila et al. 2011; Yates and Miller 2011). The economics of various supply options can be evaluated using some type of expected net present value approach, which requires that probabilities be assigned to the various climate change contingencies.

In the face of uncertainty over future climate conditions, common sense dictates constructing robust and resilient water supply and management systems than can handle a wide range of eventualities. Historical climate statistics (e.g., magnitude of the 100-year rainfall event) can no longer be relied upon for the future—stationarity is dead (Milly et al. 2008). Instead of constructing systems that perform optimally under a single or group of future climate conditions, robust decision making (RDM) focuses on identifying a set of choices that perform reasonably well compared to the alternatives across a wide range of plausible future climate scenarios (Grove and Lampert 2007). RDM employs computer simulation models to create large ensembles of possible future states that are used to identify candidate robust strategies and systematically assess their performance (Grove and Lampert 2007). The preferred adaptation strategy is the one that least frequently fails to meet performance goals.

1.11 Case Studies of Adaptation to Climate Change in High Groundwater Use Area

Chapter 13 examines projected climate changes and potential or implemented adaptative actions in some areas that have been identified as climate change hot spots or have a high dependence on groundwater—southwestern North America, High Plains of the western United States, Florida, the Mediterranean (MENA) region, and Africa. Major water suppliers in the United States (and other developed countries) generally have a high awareness of the potential impacts of climate change on their water supplies and there are numerous examples of active interactions between water suppliers and the climate change research community, such as participation in collaborative organizations (e.g., the Water Utility Climate Alliance). However, examples of implementation of actions specifically driven by climate change concerns are uncommon. Water planning tends to be driven by concerns over current climate conditions and water supplies, and the need to