RECENT STUDIES ON IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES

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Abstract

We are in a period of climate change brought about by increasing atmospheric concentrations of greenhouse gases. Atmospheric carbon dioxide levels have continually increased since the 1950s. The continuation of this phenomenon may significantly alter global and local climate characteristics, including temperature and precipitation. Changes in regional temperature and precipitation have important implications for all aspects of the hydrologic cycle. Variations in these parameters determine the amount of water that reaches the surface, evaporates or transpires back to the atmosphere, becomes stored as snow or ice, infiltrates into the groundwater system, runs off the land, and ultimately becomes base flow to streams and rivers.

While climate change affects surface water resources directly through changes in the major long-term climate variables such as air temperature, precipitation, and evapotranspiration, the relationship between the changing climate variables and groundwater is more complicated and poorly understood. The greater variability in rainfall could mean more frequent and prolonged periods of high or low groundwater levels, and saline intrusion in coastal aquifers due to sea level rise and resource reduction. This article presents the likely impact of climate change on groundwater resources and recent research studies carried out to assess the impact of climate change on groundwater resources.

Keywords: IPCC; Climate change; Hydrological cycle; Groundwater recharge; seawater intrusion; MODFLOW.

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Introduction

The Intergovernmental Panel on Climate Change (IPCC) defines climate as “the average weather in terms of the mean and its variability over a certain time-span and a certain area” and a statistically significant variation of the mean state of the climate or of its variability lasting for decades or longer, is referred to as climate change. Climate change poses uncertainties to the supply and management of water resources. The Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean surface temperature has increased 0.6 ± 0.2 ^{o}C since 1861, and predicts an increase of 2 to 4 ^{o}C over the next 100 years. Temperature increases also affect the hydrologic cycle by directly increasing evaporation of available surface water and vegetation transpiration. Consequently, these changes can influence precipitation amounts, timings and intensity rates, and indirectly impact the flux and storage of water in surface and subsurface reservoirs (i.e., lakes, soil moisture, groundwater). In addition, there may be other associated impacts, such as sea water intrusion, water quality deterioration, potable water shortage, etc.

Groundwater resources are related to climate change through the direct interaction with surface water resources, such as lakes and rivers, and indirectly through the recharge process. The direct effect of climate change on groundwater resources depends upon the change in the volume and distribution of groundwater recharge. Therefore, quantifying the impact of climate change on groundwater resources requires not only reliable forecasting of changes in the major climatic variables, but also accurate estimation of groundwater recharge.

Climate change can have profound effects on the hydrologic cycle through precipitation, evapotranspiration, and soil moisture with increasing temperatures. The hydrologic cycle will be intensified with more evaporation and more precipitation. However, the extra precipitation will be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation or major alterations in the timing of wet and dry seasons. Information on the local or regional impacts of climate change on hydrological processes and water resources is becoming more important. The effects of global warming and climatic change require multi-disciplinary research, especially when considering hydrology and global water resources.

Impact of Climate Change on Groundwater Resources

Although the most noticeable impacts of climate change could be fluctuations in surface water levels and quality, the greatest concern of water managers and government is the potential decrease and quality of groundwater supplies, as it is the main available potable water supply source for human consumption and irrigation of agriculture produce worldwide. Because groundwater aquifers are recharged mainly by precipitation or through interaction with surface water bodies, the direct influence of climate change on precipitation and surface water ultimately affects groundwater systems.

It is increasingly recognized that groundwater cannot be considered in isolation from the landscape above, the society with which it 'interacts', or from the regional hydrological cycle, but needs to be managed holistically. In understanding the likely consequences of possible future (climate and non-climate) changes on groundwater systems and the regional hydrological cycle, an important (but not exclusive) component to understand is the influence that these factors exert on recharge and runoff.

It is important to consider the potential impacts of climate change on groundwater systems. As part of the hydrologic cycle, it can be anticipated that groundwater systems will be affected by changes in recharge (which encompasses changes in precipitation and evapotranspiration), potentially by changes in the nature of the interactions between the groundwater and surface water systems, and changes in use related to irrigation.

(a) Soil Moisture

The amount of water stored in the soil is fundamentally important to agriculture and has an influence on the rate of actual evaporation, groundwater recharge, and generation of runoff. Soil moisture contents are directly simulated by global climate models, albeit over a very coarse spatial resolution, and outputs from these models give an indication of possible directions of change.

The local effects of climate change on soil moisture, however, will vary not only with the degree of climate change but also with soil characteristics. The water-holding capacity of soil will affect possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change. Climate change also may affect soil characteristics, perhaps through changes in waterlogging or cracking, which in turn may affect soil moisture storage properties. Infiltration capacity and water-holding capacity of many soils are influenced by the frequency and intensity of freezing.

(b) Groundwater Recharge and Resources

Groundwater is the major source of water across much of the world, particularly in rural areas in arid and semi-arid regions, but there has been very little research on the potential effects of climate change.

Aquifers generally are replenished by effective rainfall, rivers, and lakes. This water may reach the aquifer rapidly, through macro-pores or fissures, or more slowly by infiltrating through soils and permeable rocks overlying the aquifer. A change in the amount of effective rainfall will alter recharge, but so will a change in the duration of the recharge season. Increased winter rainfall, as projected under most scenarios for mid-latitudes, generally is likely to result in increased groundwater recharge. However, higher evaporation may mean that soil deficits persist for longer and commence earlier, offsetting an increase in total effective rainfall. Various types of aquifer will be recharged differently. The main types are unconfined and confined aquifers. An unconfined aquifer is recharged directly by local rainfall, rivers, and lakes, and the rate of recharge will be influenced by the permeability of overlying rocks and soils.

Macro-pore and fissure recharge is most common in porous and aggregated forest soils and less common in poorly structured soils. It also occurs where the underlying geology is highly fractured or is characterized by numerous sinkholes. Such recharge can be very important in some semi-arid areas. In principle, "rapid" recharge can occur whenever it rains, so where recharge is dominated by this process it will be affected more by changes in rainfall amount than by the seasonal cycle of soil moisture variability.

Shallow unconfined aquifers along floodplains, which are most common in semi-arid and arid environments, are recharged by seasonal streamflows and can be depleted directly by evaporation. Changes in recharge therefore will be determined by changes in the duration of flow of these streams, which may locally increase or decrease, and the permeability of the overlying beds, but increased evaporative demands would tend to lead to lower groundwater storage. The thick layer of sands substantially reduces the impact of evaporation.

It will be noted from the foregoing that unconfined aquifers are sensitive to local climate change, abstraction, and seawater intrusion. However, quantification of recharge is complicated by the characteristics of the aquifers themselves as well as overlying rocks and soils. A confined aquifer, on the other hand, is characterized by an overlying bed that is impermeable, and local rainfall does not influence the aquifer. It is normally recharged from lakes, rivers, and rainfall that may occur at distances ranging from a few kilometers to thousands of kilometers.

Aside from the influence of climate, recharge to aquifers is very much dependent on the characteristics of the aquifer media and the properties of the overlying soils. Several approaches can be used to estimate recharge based on surface water, unsaturated zone and groundwater data. Among these approaches, numerical modelling is the only tool that can predict recharge. Modelling is also extremely useful for identifying the relative importance of different controls on recharge, provided that the model realistically accounts for all the processes involved. However, the accuracy of recharge estimates depends largely on the availability of high quality hydrogeologic and climatic data. Determining the potential impact of climate change on groundwater resources, in particular, is difficult due to the complexity of the recharge process, and the variation of recharge within and between different climatic zones.

Attempts have been made to calculate the rate of recharge by using carbon-14 isotopes and other modeling techniques. This has been possible for aquifers that are recharged from short distances and after short durations. However, recharge that takes place from long distances and after decades or centuries has been problematic to calculate with accuracy, making estimation of the impacts of climate change difficult. The medium through which recharge takes place often is poorly known and very heterogeneous, again challenging recharge modeling. In general, there is a need to intensify research on modeling techniques, aquifer characteristics, recharge rates, and seawater intrusion, as well as monitoring of groundwater abstractions. This research will provide a sound basis for assessment of the impacts of climate change and sea-level rise on recharge and groundwater resources.

(c) Coastal Aquifers

When considering water resources in coastal zones, coastal aquifers are important sources of freshwater. However, salinity intrusion can be a major problem in these zones. Salinity intrusion refers to replacement of freshwater in coastal aquifers by saltwater. It leads to a reduction of available fresh groundwater resources. Changes in climatic variables can significantly alter groundwater recharge rates for major aquifer systems and thus affect the availability of fresh groundwater. Salinization of coastal aquifers is a function of the reduction of groundwater recharge and results in a reduction of fresh groundwater resources.

Sea-level rise will cause saline intrusion into coastal aquifers, with the amount of intrusion depending on local groundwater gradients. Shallow coastal aquifers are at greatest risk. Groundwater in low-lying islands therefore is very sensitive to change. A reduction in precipitation coupled with sea-level rise would not only cause a diminution of the harvestable volume of water; it also would reduce the size of the narrow freshwater lense. For many small island states, such as some Caribbean islands, seawater intrusion into freshwater aquifers has been observed as a result of overpumping of aquifers. Any sea-level rise would worsen the situation.

A link between rising sea level and changes in the water balance is suggested by a general description of the hydraulics of groundwater discharge at the coast. Fresh groundwater rides up over denser, salt water in the aquifer on its way to the sea (Figure 1), and groundwater discharge is focused into a narrow zone that overlaps with the intertidal zone. The width of the zone of groundwater discharge measured perpendicular to the coast, is directly proportional to the discharge rate. The shape of the water table and the depth to the freshwater/saline interface are controlled by the difference in density between freshwater and salt water, the rate of freshwater discharge and the hydraulic properties of the aquifer. The elevation of the water table is controlled by mean sea level through hydrostatic equilibrium at the shore.

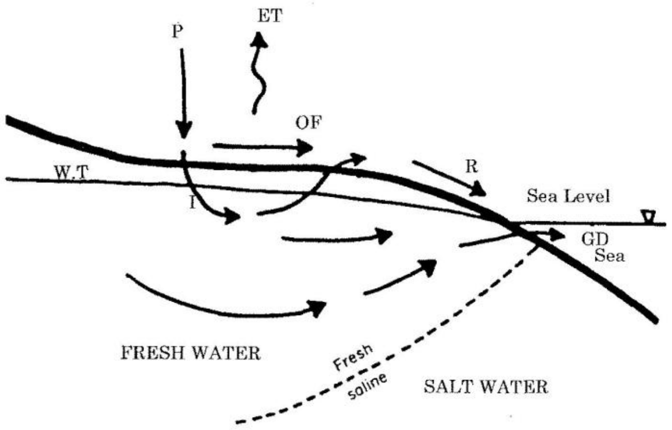

Figure 1: Conceptual Model of the Water Balance in a Coastal Watershed

To assess the impacts of potential climate change on fresh groundwater resources, we should focus on changes in groundwater recharge and sea level rise on the loss of fresh groundwater resources in water resources stressed coastal aquifers.

Recent Studies on Impact of Climate Change on Groundwater

There have been many studies relating the effect of climate changes on surface water bodies. However, very little research exists on the potential effects of climate change on groundwater, although groundwater is the major source of drinking water across much of the world and plays a vital role in maintaining the ecological value of an area. Available studies show that groundwater recharge and discharge conditions are reflection of the precipitation regime, climatic variables, landscape characteristics and human impacts such as agricultural drainage and flow regulation. Hence, predicting the behavior of recharge and discharge conditions under future climatic and other changes is of great importance for integrated water management.

Studies which consider the indirect effects derived from climate-change-induced alterations in soil, land cover, salt-water intrusion due to rising sea levels and changes in water demand are less common. These studies represent a move away from impact studies (which may be considered to be vertically integrated, in which climate change acts upon an environmental compartment) towards horizontally integrated studies in which environmental compartments interact with each other. However, they remain an incomplete assessment of the pressures facing groundwater resources associated with the direct and indirect effects of future climate and socio-economic change.

Previous studies have typically coupled climate change scenarios with hydrological models, and have generally investigated the impact of climate change on water resources in different areas. The scientific understanding of an aquifer’s response to climate change has been studied in several locations within the past decade. These studies link atmospheric models to unsaturated soil models, which, in some cases, were further linked into a groundwater model. The groundwater models used were calibrated to current groundwater conditions and stressed under different predicted climate change scenarios. Some of the recent studies (during last 10 years) on impact of climate change on groundwater resources have been discussed below.

Allen et al. (2004) used the Grand Forks aquifer, located in south-central British Columbia, Canada as a case study area for modeling the sensitivity of an aquifer to changes in recharge and river stage consistent with projected climate-change scenarios for the region. Results suggested that variations in recharge to the aquifer under the different climate-change scenarios, modeled under steady-state conditions, have a much smaller impact on the groundwater system than changes in river-stage elevation of the Kettle and Granby Rivers, which flow through the valley. All simulations showed relatively small changes in the overall configuration of the water table and general direction of groundwater flow. High-recharge and low-recharge simulations resulted in approximately a +0.05 m increase and a –0.025 m decrease, respectively, in water table elevations throughout the aquifer. Simulated changes in river-stage elevation, to reflect higher-than-peak flow levels (by 20 and 50%), resulted in average changes in the water-table elevation of 2.72 and 3.45 m, respectively. Simulated changes in river-stage elevation, to reflect lower-than-base flow levels (by 20 and 50%), resulted in average changes in the water-table elevation of -0.48 and -2.10 m, respectively. Current observed water table elevations in the valley are consistent with an average river-stage elevation (between current base flow and peak-flow stages).

Brouyere et al. (2004) developed an integrated hydrological model (MOHISE) in order to study the impact of climate change on the hydrological cycle in representative water basins in Belgium. This model considers most hydrological processes in a physically consistent way, more particularly groundwater flows which are modelled using a spatially distributed, finite-element approach. Thanks to this accurate numerical tool, after detailed calibration and validation, quantitative interpretations can be drawn from the groundwater model results. Considering IPCC climate change scenarios, the integrated approach was applied to evaluate the impact of climate change on the water cycle in the Geer basin in Belgium. The groundwater model is described in detail and results are discussed in terms of climate change impact on the evolution of groundwater levels and groundwater reserves. From the modelling application on the Geer basin, it appears that, on a pluri-annual basis, most tested scenarios predict a decrease in groundwater levels and reserves in relation to variations in climatic conditions. However, for this aquifer, the tested scenarios show no enhancement of the seasonal changes in groundwater levels.

Holman (2006) described an integrated approach to assess the regional impacts of climate and socio-economic change on groundwater recharge from East Anglia, UK. Many factors affect future groundwater recharge including changed precipitation and temperature regimes, coastal flooding, urbanization, woodland establishment, and changes in cropping and rotations. Important sources of uncertainty and shortcomings in recharge estimation were discussed in the light of the results. The uncertainty in, and importance of, socio-economic scenarios in exploring the consequences of unknown future changes were highlighted. Changes to soil properties are occurring over a range of time scales, such that the soils of the future may not have the same infiltration properties as existing soils. The potential implications involved in assuming unchanging soil properties were described.

Mall et al. (2006) examined the potential for sustainable development of surface water and groundwater resources within the constraints imposed by climate change and future research needs in India. In recent times, several studies around the globe show that climatic change is likely to impact significantly upon freshwater resources availability. In India, demand for water has already increased manifold over the years due to urbanization, agriculture expansion, increasing population, rapid industrialization and economic development. At present, changes in cropping pattern and land-use pattern, over-exploitation of water storage and changes in irrigation and drainage are modifying the hydrological cycle in many climate regions and river basins of India. An assessment of the availability of water resources in the context of future national requirements and expected impacts of climate change and its variability is critical for relevant national and regional long-term development strategies and sustainable development.

He concluded that the Indian region is highly sensitive to climate change. The elements/sectors currently at risk are likely to be highly vulnerable to climate change and variability. It is urgently required to intensify in-depth research work with the following objectives:

- Analyse recent experiences in climate variability and extreme events, and their impacts on regional water resources and groundwater availability.
- Study on changing patterns of rainfall, i.e. spatial and temporal variation and its impact on run-off and aquifer recharge pattern.
- Study sea-level rise due to increased run-off as projected due to glacial recession and increased rainfall.
- Sea-water intrusions into costal aquifers.
- Determine vulnerability of regional water resources to climate change and identify key risks and prioritize adaptation responses.
- Evaluate the efficacy of various adaptation strategies or coping mechanisms that may reduce vulnerability of the regional water resources.

It has been the endeavour of this study to summarize some important vulnerability issues associated with the present and potential future hydrological responses due to climate change and highlight those areas where further research is required. The National Environment Policy (2004) also advocated that anthropogenic climate changes have severe adverse impacts on India's precipitation patterns, ecosystems, agricultural potential, forests, water resources, coastal and marine resources. Large-scale planning would be clearly required for adaptation measures for climate change impacts, if catastrophic human misery is to be avoided.

Ranjan et al. (2006) evaluated the impacts of climate change on fresh groundwater resources specifically salinity intrusion in water resources stressed coastal aquifers. Their assessment used the Hadley Centre climate model, HadCM3 with high and low emission scenarios (SRES A2 and B2) for years 2000–2099. In both scenarios, the annual fresh groundwater resources losses indicated an increasing long-term trend in all stressed areas, except in the northern Africa/Sahara region. They also found that precipitation and temperature individually did not show good correlations with fresh groundwater loss. However, the relationship between the aridity index and fresh groundwater loss exhibited a strong negative correlation. They also discussed the impacts of loss of fresh groundwater resources on socio-economic activities, mainly population growth and per capita fresh groundwater resources.

Scibek and Allen (2006) developed a methodology for linking climate models and groundwater models to investigate future impacts of climate change on groundwater resources. An unconfined aquifer, situated near Grand Forks in south central British Columbia, Canada, was used to test the methodology. Climate change scenarios from the Canadian Global Coupled Model 1 (CGCM1) model runs were downscaled to local conditions using Statistical Downscaling Model (SDSM), and the change factors were extracted and applied in LARS-WG stochastic weather generator and then input to the recharge model. The recharge model simulated the direct recharge to the aquifer from infiltration of precipitation and consisted of spatially distributed recharge zones, represented in the Hydrologic Evaluation of Landfill Performance (HELP) hydrologic model linked to a geographic information system (GIS). A three-dimensional transient groundwater flow model, implemented in MODFLOW, was then used to simulate four climate scenarios in 1-year runs (1961–1999 present, 2010–2039, 2040–2069, and 2070-2099) and compare groundwater levels to present. The effect of spatial distribution of recharge on groundwater levels, compared to that of a single uniform recharge zone, is much larger than that of temporal variation in recharge, compared to a mean annual recharge representation. The predicted future climate for the Grand Forks area from the downscaled CGCM1 model will result in more recharge to the unconfined aquifer from spring to the summer season. However, the overall effect of recharge on the water balance is small because of dominant river-aquifer interactions and river water recharge.

Hsu et al. (2007) adopted a numerical modeling approach to investigate the response of the groundwater system to climate variability to effectively manage the groundwater resources of the Pingtung Plain. The Pingtung Plain is one of the most important groundwater-resource areas in southwestern Taiwan. The overexploitation of groundwater in the last two decades has led to serious deterioration in the quantity and quality of groundwater resources in this area. Furthermore, the manifestation of climate change tends to induce the instability of surface-water resources and strengthen the importance of the groundwater resources. Southwestern Taiwan in particular shows decreasing tendencies in both the annual amount of precipitation and annual precipitation days. A hydrogeological model was constructed based on the information from geology, hydrogeology, and geochemistry. Applying the linear regression model of precipitation to the next two decades, the modeling result shows that the lowering water level in the proximal fan raises an alarm regarding the decrease of available groundwater in the stress of climate change, and the enlargement of the low-groundwater-level area on the coast signals the deterioration of water quantity and quality in the future. Suitable strategies for water-resource management in response to hydrological impacts of future climatic change are imperative.

Jyrkama and Sykes (2007) presented a physically based methodology that can be used to characterize both the temporal and spatial effect of climate change on groundwater recharge. The method, based on the hydrologic model HELP3, can be used to estimate potential groundwater recharge at the regional scale with high spatial and temporal resolution. In this study, the method is used to simulate the past conditions, with 40 years of actual weather data, and future changes in the hydrologic cycle of the Grand River watershed. The impact of climate change is modelled by perturbing the model input parameters using predicted changes in the regions climate. The results of the study indicate that the overall rate of groundwater recharge is predicted to increase as a result of climate change. The higher intensity and frequency of precipitation will also contribute significantly to surface runoff, while global warming may result in increased evapotranspiration rates. Warmer winter temperatures will reduce the extent of ground frost and shift the spring melt from spring toward winter, allowing more water to infiltrate into the ground.

While many previous climate change impact studies have focused on the temporal changes in groundwater recharge, results of this study suggest that the impacts can also have high spatial variability.

Toews (2007) modeled the impacts of future predicted climate change on groundwater recharge resources for the arid to semi-arid south Okanagan region, British Columbia. The hydrostratigraphy of the region consists of Pleistocene-aged glaciolacustrine silt overlain by glaciofluvial sand and gravel. Spatial recharge was modelled using available soil and climate data with the HELP 3.80D hydrology model. Climate change effects on recharge were investigated using stochastically-generated climate from three GCMs. Recharge is estimated to be ~45 mm/year, with minor increases expected with climate change. However, growing season and crop water demands will increase, posing additional stresses on water use in the region. A transient MODFLOW groundwater model simulates increases of water table in future time periods, which is largely driven by irrigation application increases. Spatial recharge was also used in a groundwater model to define capture zones around eight municipal water wells. These capture zones will be used for community planning.

Woldeamlak et al. (2007) modeled the effects of climate change on the groundwater systems in the Grote-Nete catchment, Belgium, covering an area of 525 km_2, using wet (greenhouse), cold or NATCC (North Atlantic Thermohaline Circulation Change) and dry climate scenarios. Low, central and high estimates of temperature changes were adopted for wet scenarios. Seasonal and annual water balance components including groundwater recharge were simulated using the WetSpass model, while mean annual groundwater elevations and discharge were simulated with a steady-state MODFLOW groundwater model. WetSpass results for the wet scenarios showed that wet winters and drier summers are expected relative to the present situation. MODFLOW results for wet high scenario showed groundwater levels increase by as much as 79 cm, which could affect the distribution and species richness of meadows. Results obtained for cold scenarios depict drier winters and wetter summers relative to the present. The dry scenarios predict dry conditions for the whole year. There is no recharge during the summer, which is mainly attributed to high evapotranspiration rates by forests and low precipitation. Average annual groundwater levels drop by 0.5 m, with maximum of 3.1 m on the eastern part of the Campine Plateau. This could endanger aquatic ecosystem, shrubs, and crop production.

Carneiro et al. (2008) applied a density dependent numerical flow model (FEMWATER) to study the climate change impact in an unconfined shallow aquifer in the Mediterranean coast of Morocco. The stresses imposed to the model were derived from the IPCC emission scenarios and included recharge variations, rising sea level and advancing seashore. The simulations show that there will be a significant decline in the renewable freshwater resources and that salinity increases can be quite large but are limited to a restricted area.

Dragoni and Sukhija (2008) analysed the main methods for studying the relationships between climate change and groundwater, and presented the main areas in which hydrogeological research should focus in order to mitigate the likely impacts. There is a general consensus that climate change is an ongoing phenomenon. This will inevitably bring about numerous environmental problems, including alterations to the hydrological cycle, which is already heavily influenced by anthropogenic activity. The available climate scenarios indicate areas where rainfall may increase or diminish, but the final outcome with respect to man and environment will, generally, be detrimental. Groundwater will be vital to alleviate some of the worst drought situations.

Herrera-Pantoja and Hiscock (2008) outlined a methodology to quantify the effects of climate change on potential groundwater recharge (or hydrological excess water) for three locations in the north and south of Great Britain. Using results from a stochastic weather generator, actual evapotranspiration and potential groundwater recharge time-series for the historic baseline 1961-1990 and for a future ‘high’ greenhouse gas emissions scenario for the 2020s, 2050s and 2080s time periods were simulated for Coltishall in East Anglia, Gatwick in southeast England and Paisley in west Scotland. Under the ‘high’ gas emissions scenario, results showed a decrease of 20% in potential groundwater recharge for Coltishall, 40% for Gatwick and 7% for Paisley by the end of this century. The persistence of dry periods is shown to increase for the three sites during the 2050s and 2080s. Gatwick presents the driest conditions, Coltishall the largest variability of wet and dry periods and Paisley little variability. For Paisley, the main effect of climate change is evident during the dry season (April-September), when the potential amount of hydrological excess water decreases by 88% during the 2080s. Overall, it is concluded that future climate may present a decrease in potential groundwater recharge that will increase stress on local and regional groundwater resources that are already under ecosystem and water supply pressures.

Franssen (2009) indicated the limitations of the studies that address the impact of climate change on groundwater resources and suggested an improved approach. A general review, both from a groundwater hydrological and a climatological viewpoint, is given, oriented on the impact of climate change on groundwater resources. The impact of climate change on groundwater resources is not the subject of many studies in the scientific literature. Only rarely sophisticated downscaling techniques are applied to downscale estimated global circulation model (GCM) future precipitation series for a point or region of interest. Often it is not taken into account that different climate models calculate considerably different precipitation amounts (conceptual uncertainty). The joint downscaling of the meteorological variables that govern potential evapotranspiration (ET) is never done in the context of a study that assessed the impact of climate change on groundwater resources. It is desirable that actual ET is calculated in (groundwater) hydrological models on a physical basis, i.e. by coupling the energy and water balance at the Earth's surface.

Holman et al. (2009) indicated that groundwater resource estimates require the calculation of recharge using a daily time step. Within climate-change impact studies, this inevitably necessitates temporal downscaling of global or regional climate model outputs. This paper compares future estimates of potential groundwater recharge calculated using a daily soil-water balance model and climate-change weather time series derived using change factor (deterministic) and weather generator (stochastic) methods for Coltishall, UK. The uncertainty in the results for a given climate-change scenario arising from the choice of downscaling method is greater than the uncertainty due to the emissions scenario within a 30-year time slice. Robust estimates of the impact of climate change on groundwater resources require stochastic modelling of potential recharge, but this has implications for groundwater model runtimes. It is recommended that stochastic modelling of potential recharge is used in vulnerable or sensitive groundwater systems, and that the multiple recharge time series are sampled according to the distribution of contextually important time series variables, e.g. recharge drought severity and persistence (for water resource management) or high recharge years (for groundwater flooding). Such an approach will underpin an improved understanding of climate change impacts on sustainable groundwater resource management based on adaptive management and risk-based frameworks.

Shah (2009) reviewed the India's opportunities for mitigation and adaptation with reference to climate change and groundwater. For millennia, India used surface storage and gravity flow to water crops. During the last 40 years, however, India has witnessed a decline in gravity-flow irrigation and the rise of a booming 'water-scavenging' irrigation economy through millions of small, private tubewells. For India, groundwater has become at once critical and threatened. Climate change will act as a force multiplier; it will enhance groundwater's criticality for drought-proofing agriculture and simultaneously multiply the threat to the resource. Groundwater pumping with electricity and diesel also accounts for an estimated 16–25 million mt of carbon emissions, 4–6% of India's total. From a climate change point of view, India's groundwater hotspots are western and peninsular India. These are critical for climate change mitigation as well as adaptation. To achieve both, India needs to make a transition from surface storage to 'managed aquifer storage' as the center pin of its water strategy with proactive demand- and supply-side management components. In doing this, India needs to learn intelligently from the experience of countries like Australia and the United States that have long experience in managed aquifer recharge.

Allen (2010) examined historical groundwater levels for selected observation wells in the south coastal region of British Columbia, Canada, to gain a better understanding of historical trends. Over a common period (1976-1999), negative trends in groundwater level dominate most records, and appear to be related to longer term negative regional trends in precipitation, although variable trends are evident at the shorter time periods used for this study. To explore potential consequences of varying recharge on groundwater quality, water chemistry data from selected monitoring wells on one island were examined. Chloride concentrations were observed to vary annually in one well by up to 4000 mg/L. Projections for future climate from one global climate model (CGCM1) were used as input to a recharge model to study the sensitivity of recharge to shifts in precipitation and temperature predicted for the region. The recharge model was driven by a stochastic daily weather series, calibrated to historic climate data. Daily weather series represent historic climate, and two future time periods (2020s) and (2050s). Simulated recharge increases progressively in the future using this particular global climate model; however, precipitation projections for this region of British Columbia are highly uncertain. Both positive and negative shifts in annual precipitation were predicted using a range of global climate models.

Allen et al. (2010) addressed variations in the prediction of recharge by comparing recharge simulated using climate data generated using a state-of-the-art downscaling method, TreeGen, with a range of global climate models (GCMs). The study site is the transnational Abbotsford-Sumas aquifer in coastal British Columbia, Canada and Washington State, USA, and is representative of a wet coastal climate. Sixty-four recharge zones were defined based on combinations of classed soil permeability, vadose zone permeability, and unsaturated zone depth (or depth to water table) mapped in the study area. One-dimensional recharge simulations were conducted for each recharge zone using the HELP hydrologic model, which simulates percolation through a vertical column. The HELP model is driven by mean daily temperature, daily precipitation, and daily solar radiation. For the historical recharge simulations, the climate data series was generated using the LARS-WG stochastic weather generator. Historical recharge was compared to recharge simulated using climate data series derived from the TreeGen downscaling model for three future time periods: 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099) for each of four GCMs (CGCM3.1, ECHAM5, PCM1, and CM2.1). Recharge results are compared on an annual basis for the entire aquifer area. Both increases and decreases relative to historical recharge are simulated depending on time period and model. By the 2080s, the range of model predictions spans −10.5% to +23.2% relative to historical recharge. This variability in recharge predictions suggests that the seasonal performance of the downscaling tool is important and that a range of GCMs should be considered for water management planning.

Crosbie et al. (2010) presented a methodology for assessing the average changes in groundwater recharge under a future climate. The method is applied to the 1,060,000 km^2 Murray-Darling Basin (MDB) in Australia. Climate sequences were developed based upon three scenarios for a 2030 climate relative to a 1990 climate from the outputs of 15 global climate models. Dryland diffuse groundwater recharge was modelled in WAVES using these 45 climate scenarios and fitted to a Pearson Type III probability distribution to condense the 45 scenarios down to three: a wet future, a median future and a dry future. The use of a probability distribution allowed the significance of any change in recharge to be assessed. This study found that for the median future, climate recharge is projected to increase on average by 5% across the MDB but this is not spatially uniform. In the wet and dry future scenarios the recharge is projected to increase by 32% and decrease by 12% on average across the MDB, respectively. The differences between the climate sequences generated by the 15 different global climate models makes it difficult to project the direction of the change in recharge for a 2030 climate, let alone the magnitude.

Dams et al. (2010) presented a methodology to predict the potential impact of climate change on quantitative groundwater characteristics determining GWDTEs (Groundwater Dependent Terrestrial Ecosystems). The developed methodology includes coupling a distributed hydrological model (WetSpa) with a transient groundwater flow model (MODFLOW) and is tested for the Kleine Nete basin, Belgium. Because the occurrence of phreatophytes is strongly determined by the dynamic properties of the groundwater system, a groundwater flow model with a high temporal and spatial distribution was developed using MODFLOW. The groundwater recharge and river heads are estimated with the WetSpa model using a daily time step to incorporate the impact of changes in rainfall intensity. Potential future hydrological changes are calculated by comparing the hydrological state corresponding to 1960-1991 with future scenarios developed for 2070-2101.

Since the uncertainty in the prediction of the future climate components such as potential evapotranspiration (PET) and precipitation is still high, an ensemble of 28 climate scenarios were chosen from the PRUDENCE database. For each of these scenarios, recharge, river stage, groundwater head and groundwater flow are estimated for 32 years with half monthly time steps. Comparison of the original measured PET with future PET shows that the PET during summer rises in all future scenarios with about 1 mm per day. For winter conditions the scenarios predict little change in PET. Future precipitation shows an increase in precipitation during winter and a decrease during summer. Future groundwater recharge decreases on average with 20 mm per year, the highest decreases are simulated from July until September. Average groundwater heads indicate an average decrease of 7 cm. Groundwater levels in interfluves generally show decreases up to 30 cm. The mean lowest groundwater level decreases on average with 6 cm, while the mean highest groundwater level decreases about 3 cm. On average, the groundwater discharge reduces with 4%, from 5 to 4.8 m³/s. GWDTEs that currently receive a low groundwater discharge, are likely to disappear due to future climate changes.

McCallum et al. (2010) used a sensitivity analysis of climate variables using a modified version of WAVES, a soil-vegetation-atmosphere-transfer model (unsaturated zone), to determine the importance of each climate variable in the change in groundwater recharge for three points in Australia. This study found that change in recharge is most sensitive to change in rainfall. Increases in temperature and changes in rainfall intensity also led to significant changes in recharge. Although not as significant as other climate variables, some changes in recharge were observed due to changes in solar radiation and carbon dioxide concentration. When these variables were altered simultaneously, changes in recharge appeared to be closely related to changes in rainfall; however, in nearly all cases, recharge was greater than would have been predicted if only rainfall had been considered. These findings have implications for how recharge is projected to change due to climate change.

Okkonen et al. (2010) presented a literature review of the impacts of anticipated climate change on unconfined aquifers, along with a conceptual framework for evaluating the complex responses of surface and subsurface hydrology to climate variables in cold regions. The framework offers a way to conceptualize how changes in one component of the system may impact another by delineating the relationships among climate drivers, hydrological responses, and groundwater responses in a straight-forward manner. The model is elaborated in the context of shallow unconfined aquifers in the boreal environment of Finland. In cold conditions, climate change is expected to reduce snow cover and soil frost and increase winter floods. The annual surface water level maximum will occur earlier in spring, and water levels will decrease in summer due to higher evapotranspiration rates. The maximum recharge and groundwater level are expected to occur earlier in the year. Lower groundwater levels are expected in summer due to higher evapotranspiration rates. The flow regimes between shallow unconfined aquifers and surface water may change, affecting water quantity and quality in the surface and groundwater systems.

Oude Essink et al. (2010) focussed on a coastal groundwater system that is already threatened by a relatively high seawater level: the low-lying Dutch Delta. Nearly one third of the Netherlands lies below mean sea level, and the land surface is still subsiding up to 1 m per century. This densely populated delta region, where fresh groundwater resources are used intensively for domestic, agricultural, and industrial purposes, can serve as a laboratory case for other low-lying delta areas throughout the world. Their findings on hydrogeological effects can be scaled up since the problems the Dutch face now will very likely be the problems encountered in other delta areas in the future. They calculated the possible impacts of future sea level rise, land subsidence, changes in recharge, autonomous salinization, and the effects of two mitigation counter-measures with a three-dimensional numerical model for variable density groundwater flow and coupled solute transport (MOCDENS3D). They considered the effects on hydraulic heads, seepage fluxes, salt loads to surface waters, and changes in fresh groundwater resources as a function of time and for seven scenarios.

Their numerical modeling results show that the impact of sea level rise is limited to areas within 10 km of the coastline and main rivers because the increased head in the groundwater system at the coast can easily be produced though the highly permeable Holocene confining layer. Along the southwest coast of the Netherlands, salt loads will double in some parts of the deep and large polders by the year 2100 A.D. due to sea level rise. More inland, ongoing land subsidence will cause hydraulic heads and phreatic water levels to drop, which may result in damage to dikes, infrastructure, and urban areas. In the deep polders more inland, autonomous upconing of deeper and more saline groundwater will be responsible for increasing salt loads. The future increase of salt loads will cause salinization of surface waters and shallow groundwater and put the total volumes of fresh groundwater volumes for drinking water supply, agricultural purposes, industry, and ecosystems under pressure.

Payne (2010) observed that sea-level rise and changes in precipitation patterns may contribute to the occurrence and affect the rate of saltwater contamination in the Hilton Head Island, South Carolina area. To address the effects of climate change on saltwater intrusion, a three-dimensional, finite-element, variable-density, solute-transport model (SUTRA 2.1) was developed to simulate different rates of sea-level rise and variation in onshore freshwater recharge. Model simulation showed that the greatest effect on the existing saltwater plume occurred from reducing recharge, suggesting recharge may be a more important consideration in saltwater intrusion management than estimated rates of sea-level rise. Saltwater intrusion management would benefit from improved constraints on recharge rates by using model-independent, local precipitation and evapotranspiration data, and improving estimates of confining unit hydraulic properties.

Rozell and Wong (2010) investigated the effects of climate change on Shelter Island, New York State (USA), a small sandy island, using a variable-density transient groundwater flow model (SEAWAT). Predictions for changes in precipitation and sea-level rise over the next century from the Intergovernmental Panel on Climate Change 2007 report were used to create two future climate scenarios. In the scenario most favorable to fresh groundwater retention, consisting of a 15% precipitation increase and 0.18-m sea-level rise, the result was a 23-m seaward movement of the freshwater/ salt-water interface, a 0.27-m water-table rise, and a 3% increase in the fresh-water lens volume. In the scenario supposedly least favorable to groundwater retention, consisting of a 2% precipitation decrease and 0.61-m sea-level rise, the result was a 16-m landward movement of the fresh-water/salt-water interface, a 0.59-m watertable rise, and a 1% increase in lens volume. The unexpected groundwater-volume increase under unfavorable climate change conditions was best explained by a clay layer under the island that restricts the maximum depth of the aquifer and allows for an increase in freshwater lens volume when the water table rises.

Vandenbohede and Lebbe (2010) evaluated the effects of sea level rise and future recharge changes on the coastal aquifer of the western Belgian coastal plain with a 3D density dependent groundwater flow model (MOCDENS3D). The area is characterised by a wide dune belt. Sea level rise results in a landward enlargement of the fresh water lens under the dunes and an increase of flow towards the dune-polder transition's drainage system. Recharge increase results also in an enlargement of the dune's fresh water lens and an increase of the amount of water which must be evacuated by the polder's drainage system. Recharge decrease has the reverse effect.

Zhou et al. (2010) reported that climate change affects not only water resources but also water demand for irrigation. A large proportion of the world's agriculture depends on groundwater, especially in arid and semi-arid regions. In several regions, aquifer resources face depletion. Groundwater recharge has been viewed as a by-product of irrigation return flow, and with climate change, aquifer storage of such flow will be vital. A general review, for a broadbased audience, is given of work on global warming and groundwater resources, summarizing the methods used to analyze the climate change scenarios and the influence of these predicted changes on groundwater resources around the world (especially the impact on regional groundwater resources and irrigation requirements). Future challenges of adapting to climate change are also discussed. Such challenges include water-resources depletion, increasing irrigation demand, reduced crop yield, and groundwater salinization. The adaptation to and mitigation of these effects is also reported, including useful information for water-resources managers and the development of sustainable groundwater irrigation methods. Rescheduling irrigation according to the season, coordinating the groundwater resources and irrigation demand, developing more accurate and complete modeling prediction methods, and managing the irrigation facilities in different ways would all be considered, based on the particular cases.

Barthel (2011) presented an integrated approach for assessing the availability of groundwater under conditions of 'global-change'. The approach is embedded in the DANUBIA system developed by the interdisciplinary GLOWA-Danube Project to simulate the interaction of natural and socio-economic processes within the Upper Danube Catchment (UDC, 77,000 km^2 and located in parts of Germany, Austria, Switzerland and Italy). The approach enables the quantitative assessment of groundwater bodies (zones), which are delineated by intersecting surface watersheds, regional aquifers, and geomorphologic regions. The individual hydrogeological and geometrical characteristics of these zones are accounted for by defining characteristic response times and weights to describe the relative significance of changes in variables (recharge, groundwater level, groundwater discharge, river discharge) associated with different states. These changes, in each zone, are converted into indices (*GroundwaterQuantityFlags*). The motivation and particularities of regional-scale groundwater assessment and the background of GLOWA-Danube are described, along with a description of the developed methodology. The approach was applied to the UDC, where several different climate scenarios (2011–2060) were evaluated. A selection of results is presented to demonstrate the potential of the methodology. The approach was inspired by the European Water Framework Directive, yet it has a stronger focus on the evaluation of global-change impacts.

Yihdego and Webb (2011) carried out modeling of bore hydrographs to determine the impact of climate and land-use change in a temperate subhumid region of southeastern Australia. To determine the relative impact of climate and human intervention on groundwater elevations in western Victoria, southeast Australia, bore hydrograph fluctuations in three aquifers were modelled using a transfer function noise model (PIRFICT) and an auto-regressive model (HARTT), which give generally comparable results. Most of the groundwater-level fluctuations (>90%) are explained by climatic variation, particularly rainfall. The overall non-climate-related trend in groundwater level is downward and small but statistically significant (−0.04 to −0.066 m/yr), and is probably due to the widespread replacement of grazing land by wheat and canola cultivation, as these crops use more water than pasture. A large non-climate-related trend (−0.30 m/yr) for bores in an irrigation area is mainly related to groundwater extraction. The response time of the system is rapid (only 4.85 years on average), much faster than previously estimated. Rates of groundwater flow are much slower; groundwater ages are up to ~35,000 years. Response times effectively represent the time for the system to move to a new state of hydrologic equilibrium; this prediction of the time scale of the impacts of land-use change on groundwater resources will allow the development of better strategies for groundwater management.

Crosbie et al. (2012) investigated episodic recharge with reference to climate change in the Murray-Darling Basin, Australia. In semi-arid areas, episodic recharge can form a significant part of overall recharge, dependant upon infrequent rainfall events. With climate change projections suggesting changes in future rainfall magnitude and intensity, groundwater recharge in semi-arid areas is likely to be affected disproportionately by climate change. This study sought to investigate projected changes in episodic recharge in arid areas of the Murray-Darling Basin, Australia, using three global warming scenarios from 15 different global climate models (GCMs) for a 2030 climate. Two metrics were used to investigate episodic recharge: at the annual scale the coefficient of variation was used, and at the daily scale the proportion of recharge in the highest 1% of daily recharge. The metrics were proportional to each other but were inconclusive as to whether episodic recharge was to increase or decrease in this environment; this is not a surprising result considering the spread in recharge projections from the 45 scenarios. The results showed that the change in the low probability of exceedance rainfall events was a better predictor of the change in total recharge than the change in total rainfall, which has implications for the selection of GCMs used in impact studies and the way GCM results are downscaled.

Neukum and Azzam (2012) investigated the impact of climate change on groundwater recharge in a small catchment in the Black Forest, Germany. Temporal and spatial changes of the hydrological cycle are the consequences of climate variations. In addition to changes in surface runoff with possible floods and droughts, climate variations may affect groundwater through alteration of groundwater recharge with consequences for future water management. This study investigates the impact of climate change, according to the Special Report on Emission Scenarios (SRES) A1B, A2 and B1, on groundwater recharge in the catchment area of a fissured aquifer in the Black Forest, Germany, which has sparse groundwater data. The study uses a water-balance model considering a conceptual approach for groundwater-surface water exchange. River discharge data are used for model calibration and validation. The results show temporal and spatial changes in groundwater recharge. Groundwater recharge is progressively reduced for summer during the twenty-first century. The annual sum of groundwater recharge is affected negatively for scenarios A1B and A2. On average, groundwater recharge during the twenty-first century is reduced mainly for the lower parts of the valley and increased for the upper parts of the valley and the crests. The reduced storage of water as snow during winter due to projected higher air temperatures causes an important relative increase in rainfall and, therefore, higher groundwater recharge and river discharge.

Raposo et al. (2013) assessed the impact of future climate change on groundwater recharge in Galicia-Costa, Spain. Climate change can impact the hydrological processes of a watershed and may result in problems with future water supply for large sections of the population. Results from the FP5 PRUDENCE project suggest significant changes in temperature and precipitation over Europe. In this study, the Soil and Water Assessment Tool (SWAT) model was used to assess the potential impacts of climate change on groundwater recharge in the hydrological district of Galicia-Costa, Spain. Climate projections from two general circulation models and eight different regional climate models were used for the assessment and two climate-change scenarios were evaluated. Calibration and validation of the model were performed using a daily time-step in four representative catchments in the district. The effects on modeled mean annual groundwater recharge are small, partly due to the greater stomatal efficiency of plants in response to increased CO_2 concentration. However, climate change strongly influences the temporal variability of modeled groundwater recharge. Recharge may concentrate in the winter season and dramatically decrease in the summer–autumn season. As a result, the dry-season duration may be increased on average by almost 30 % for the A2 emission scenario, exacerbating the current problems in water supply.

Lapworth et al. (2013) estimated residence times of shallow groundwater in West Africa. Although shallow groundwater (<50 mbgl) sustains the vast majority of improved drinking-water supplies in rural Africa, there is little information on how resilient this resource may be to future changes in climate. This study presents results of a groundwater survey using stable isotopes, CFCs, SF_6, and ^3H across different climatic zones (annual rainfall 400–2,000 mm/year) in West Africa. The purpose was to quantify the residence times of shallow groundwaters in sedimentary and basement aquifers, and investigate the relationship between groundwater resources and climate. Stable-isotope results indicate that most shallow groundwaters are recharged rapidly following rainfall, showing little evidence of evaporation prior to recharge. Chloride mass-balance results indicate that within the arid areas (<400 mm annual rainfall) there is recharge of up to 20 mm/year. Age tracers show that most groundwaters have mean residence times (MRTs) of 32–65 years, with comparable MRTs in the different climate zones. Similar MRTs measured in both the sedimentary and basement aquifers suggest similar hydraulic diffusivity and significant groundwater storage within the shallow basement. This suggests there is considerable resilience to short-term inter-annual variation in rainfall and recharge, and rural groundwater resources are likely to sustain diffuse, low volume abstraction.

Mollema and Antonellini (2013) investigated seasonal variation in natural recharge of coastal aquifers. Many coastal zones around the world have irregular precipitation throughout the year. This results in discontinuous natural recharge of coastal aquifers, which affects the size of freshwater lenses present in sandy deposits. Temperature data for the period 1960–1990 from LocClim (local climate estimator) and those obtained from the Intergovernmental Panel on Climate Change (IPCC) SRES A1b scenario for 2070–2100, have been used to calculate the potential evapotranspiration with the Thornthwaite method. Potential recharge (difference between precipitation and potential evapotranspiration) was defined at 12 locations: Ameland (The Netherlands), Auckland and Wellington (New Zealand); Hong Kong (China); Ravenna (Italy), Mekong (Vietnam), Mumbai (India), New Jersey (USA), Nile Delta (Egypt), Kobe and Tokyo (Japan), and Singapore. The influence of variable/discontinuous recharge on the size of freshwater lenses was simulated with the SEAWAT model. The discrepancy between models with continuous and with discontinuous recharge is relatively small in areas where the total annual recharge is low (258–616 mm/year); but in places with Monsoon-dominated climate (e.g. Mumbai, with recharge up to 1,686 mm/year), the difference in freshwater-lens thickness between the discontinuous and the continuous model is larger (up to 5 m) and thus important to consider in numerical models that estimate freshwater availability.

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Concluding Remarks

These studies are still at infancy and more data, in terms of field information are to be generated. This will also facilitate appropriate validation of the simulation for the present scenarios. In summary, climate change is likely to have an impact on future recharge rates and hence on the underlying groundwater resources. The impact may not necessarily be a negative one, as evidenced by some of the investigations. Quantifying the impact is difficult, however, and is subject to uncertainties present in the future climate predictions. Simulations based on general circulation models (GCMs) have yielded mixed and conflicting results, raising questions about their reliability in predicting future hydrologic conditions. However, it is clear that the global warming threat is real and the consequences of climate change phenomena are many and alarming. If the likely consequences of future changes of groundwater recharge, resulting from both climate and socio-economic change, are to be assessed, hydrogeologists must increasingly work with researchers from other disciplines, such as socio-economists, agricultural modelers and soil scientists.

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