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Review papers

A synopsis of climate change effects on groundwater recharge

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ABSTRACT

Six review articles published between 2011 and 2016 on groundwater and climate change are briefly summarized. This synopsis focuses on aspects related to predicting changes to groundwater recharge conditions, with several common conclusions between the review articles being noted. The uncertainty of distribution and trend in future precipitation from General Circulation Models (GCMs) results in varying predictions of recharge, so much so that modelling studies are often not able to predict the magnitude and direction (increase or decrease) of future recharge conditions. Evolution of modelling approaches has led to the use of multiple GCMs and hydrologic models to create an envelope of future conditions that reflects the probability distribution. The choice of hydrologic model structure and complexity, and the choice of emissions scenario, has been investigated and somewhat resolved; however, recharge results remain sensitive to downscaling methods. To overcome uncertainty and provide practical use in water management, the research community indicates that modelling at a mesoscale, somewhere between watersheds and continents, is likely ideal. Improvements are also suggested for incorporating groundwater processes within GCMs.

Contents

1. Background

Groundwater recharge is the result of an intricate relationship between energy and moisture occurring in the critical zone between the atmosphere and subsurface. The recharge process governs downward fluid flux across the water table, and relates the climate, vegetation, and subsurface characteristics for a given area. Thus, an understanding of the recharge process, including rates, timing and location, is important for hydrogeological characterization and groundwater resource assessment. However, recharge is challenging to measure directly (Scanlon et al., 2002), leading to an inherent uncertainty when trying to develop aquifer budgets, investigate groundwater vulnerability and migration of nutrients, and determine the impact of changes in land cover and climate.

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Global climate change – the alteration of long-term climate patterns – will have an impact on ecosystems, economies and communities. The Intergovernmental Panel on Climate Change (IPCC) acknowledged that groundwater use will increase as a result of the declining availability of surface water and increased global water consumption (IPCC, 2007). Arguably, uncertainty of the recharge process will be compounded with uncertainty associated with predicting future climate scenarios. The IPCC Fourth Assessment Report identified a gap in the knowledge of the impact of climate change on groundwater resources (Kundzewicz et al., 2007) that triggered new work on climate change and groundwater. The results of several studies emerged in peer-reviewed hydrologic journals beginning in about 2009, with scientific reviews on the topic published between 2011 and 2016. The paucity of groundwater and climate change research drove a significant increase in publications following the IPCC Fourth Assessment Report.

The aim of this short paper is to provide a synopsis of recent review articles pertaining to groundwater and climate change, with a focus on predicting changes to recharge conditions. Six articles are identified, which provide a comprehensive coverage of groundwater and climate change. Each of these articles has a thorough review of the science, processes and case studies related to climate change and groundwater recharge. This synopsis does not aim to replicate these excellent review articles, but rather to provide an overview and context for the Special Issue on Aquifers Recharge. The articles identified in this synopsis contain extensive reference lists on groundwater and climate change.

2. Reviews of groundwater and climate change

2.1. *Green et al. (2011)*

The first comprehensive review of processes relating climate change and groundwater was by Green et al. (2011), who described the challenge of understanding and predicting a number of interrelated variables in space and time. This review provided an account of growing interest in the subject following the IPCC Fourth Assessment Report, an examination of General Circulation Models (GCMs) and future projections, and a very thorough description of groundwater processes. The review also documented many observational techniques spanning isotopic, geochemical, geophysical and remote sensing methods that could be useful in observing large-scale changes in groundwater.

Green et al. (2011) described several of the first studies that attempted to quantitatively link climate (or weather) models with hydrologic models. The authors noted that numerical models are essential to develop an understanding of system dynamics and simulate realistic responses of groundwater conditions. From approximately 2000–2009, the complexity of modelling increased to represent coupled processes and the growing realization that multiple GCMs were needed due to their varying predictions. Arguably, this trend of increasing complexity has continued to the present day. The review identified that different modelling approaches required further investigation for applicability to climate change. Semi-distributed or lumped models provide efficiency for large regions aligned with the same scale as GCMs, while deterministic distributed models might better honour localized features. The authors noted that future projections of climate and interaction with groundwater are required at the scale of application, somewhere between global and local scales.

2.2. *Taylor et al. (2013)*

The global review by Taylor et al. (2013) integrated the understanding of direct and indirect impacts of climate on groundwater, and examined specifically how future climate scenarios are represented using GCMs. This review confirms that the relationship between climate and groundwater is complex, with different feedback mechanisms occurring in different parts of the world. The role of vegetation is shown to be paramount for the recharge process, where change in precipitation could be accommodated by natural adjustment in evapotranspiration in some cases. Another example of intricate feedback is the anticipated shift in mountain hydrologic cycles, where changes in the timing of snowpack melt will result in potentially longer and lower low-flow periods for streams and rivers. In-turn, change in mountain hydrologic cycles will have an effect on adjacent valley aquifer systems.

Taylor et al. (2013) found that groundwater studies utilizing GCMs have heeded the advice of Holman et al. (2012), whereby multiple GCMs are used to develop an envelope of future climate conditions. However, the review also noted that the land surface modelling component of climate modelling typically neglected groundwater. In this regard, the climate modelling community has not connected the atmosphere dynamically with the subsurface, especially to account for lateral movement of groundwater. Taylor et al. (2013) described that many studies show a strong connection between the atmosphere and groundwater where water table depths are less than 7 m, which has opened up research in this ‘critical zone’ where groundwater may have influence on land-energy fluxes. The review echoes the common opinion that when used for future climate scenarios, the dominant source of uncertainty was found to be the projections of derived from GCMs.

In looking forward, Taylor et al. (2013) reiterate the expected future demand for groundwater since it can enhance resilience of water supplies under a changing climate. The authors noted that attaining sustainable goals will rely on innovative management approaches and groundwater observations. Generally, the lack of groundwater observations not only makes it difficult to inform management decisions, but also limits the scientific understanding and evaluation of climate and hydrologic simulation models. The review identified groundwater storage as a global knowledge gap, which varies regionally and underpins local response to climate change.

2.3. *Meixner et al. (2016)*

One of the most recent reviews about groundwater and climate change is the assessment of eight representative aquifer systems across the western United States by Meixner et al. (2016). This significant body of work brought together the conceptual understanding and estimation of future recharge conditions by considering how changes in temperature and precipitation would likely change recharge. By reviewing recharge mechanisms and structuring a systematic approach to present future scenarios, Meixner et al. (2016) offer a way to bridge the spatial gap between the global process of climate change and more localized impact to specific aquifer systems. This review found that there were limited studies where climate projections have been quantitatively coupled with recharge estimation (e.g. using numerical models), and that model-based projections were only available for four of the eight aquifer systems for the western United States. The review identified that the most significant change will be decreasing snowpack and the long-term (transient) response of mountain system recharge, which will have an impact on lower elevation valley aquifer systems. Using the eight regional aquifer systems, Meixner et al. (2016) demonstrated that the greatest challenge in estimating future recharge is associated with the difficulty predicting changes to the frequency and intensity of precipitation. The authors concluded that there is a need for climate models that quantitatively integrate future climate with recharge mechanisms and groundwater flow paths to realistically propagate changes through the regional aquifer systems.

3. Modelling future recharge conditions

3.1. *Kurylyk and MacQuarrie (2013)*

The summary of research on climate change and groundwater recharge by Kurylyk and MacQuarrie (2013) described the evolution of modelling approaches from 2006 to 2013. During this period, multiple downscaled climate scenarios emerged in studies to establish an envelope of recharge possibilities (e.g. Crosbie et al., 2011), including use of multiple models (GCM and hydrologic) and multiple emissions scenario. Using a case study catchment from eastern Canada, Kurylyk and MacQuarrie (2013) examined the uncertainty in recharge driven from varying: (i) GCMs; (ii) emissions scenario; and (iii) downscaling methods. They demonstrated that although uncertainty is associated with each, future recharge was most sensitive to the downscaling method and least sensitive to the emissions scenario. Similar to other studies, they concluded that it is difficult to predict the magnitude and direction of change in groundwater recharge (i.e. increase or decrease). Kurylyk and MacQuarrie (2013) proposed that groundwater recharge be directly simulated within the land surface models of GCMs (e.g. Maxwell and Kollet, 2008), and that more attention be paid to downscaling GCM results to regions of interest. To support improved representation in models, they also noted a need for longer-term hydrologic observatories to quantify relation between climate and groundwater.

3.2. *Crosbie et al. (2013a)*

Acknowledging that different GCMs and downscaling methods can produce a wide range of results for future recharge conditions, Crosbie et al. (2013a) explored a method of post-processing recharge modelling results so as to better communicate highly uncertain findings. They generated 48 future climate scenarios using 16 GCMs for the Australian continent and simulated recharge for specific points representative of various climate zones. The resultant recharge fluxes demonstrated no consensus in magnitude and direction (increase or decrease) of future recharge conditions for much of Australia, except for localized areas where the GCMs shared similar future conditions. Faced with such a wide range of results, utilizing the findings would be difficult for water management in any given region. In an attempt to overcome the uncertainty, Crosbie et al. (2013a) fit the simulated recharge results to a probability distribution that helped analyze results and compare across multiple regions. This approach has also been applied to a large aquifer system in the U.S. (Crosbie et al., 2013b) and could guide others in aggregating the results of multi-model studies.

3.3. *Moeck et al. (2016)*

While the variability of GCM projections has been established, Moeck et al. (2016) investigated hydrological model structure and described how uncertainty can propagate (and increase) in hydrological models when quantifying future rates of groundwater recharge. Moeck et al. (2016) defined four categories of modelling approaches to simulate groundwater recharge: (i) simple empirical relationships; (ii) soil water balance models (bucket models); (iii) soil water balance models coupled to groundwater models; and (iv) Richards' equation models. Several previous studies identified that the choice of a model to simulate recharge strongly influences the simulation outcome (e.g. Crosbie et al., 2011); however, the focus of Moeck et al. (2016) was to systematically evaluate choices in model structure and the consequence when simulating the recharge process.

Moeck et al. (2016) use a 2D reference model to evaluate choice of model structure when simulating recharge. They found that 1D homogenous models best reproduce the reference case, and that incorporating layered heterogeneity resulted in only minor improvement. Presumably, 1D recharge is governed by the least permeable subsurface layer. They also found that the simpler model structures lead to differing recharge rates under extreme climate conditions. In this regard, simple empirical relationships and soil water balance models are not able to represent conditions outside the normal range of use because the physical recharge process is not simulated rigorously. While these approaches may be valid for temperate and humid regions where gravity drainage is dominant, they do not account for dynamic moisture movement in deeper vadose zones of less humid regions. With a thicker unsaturated zone comes the opportunity for vertical movement of water (both upward and downward) before recharge to the saturated zone can occur (i.e. movement of the zero flux plane).

Moeck et al. (2016) reiterate the recommendation that capturing climate extremes is critical when developing models, both in terms of adequately calibrating a model and improving the conceptual understanding of system dynamics. From the findings of their study, they suggested that although variability in simulated future recharge conditions is introduced by choice of model structure, the more dominant controlling factor is the choice of future climate scenario. Moeck et al. (2016) recommend extending the concept of ensemble modelling to include hydrologic models, where an ensemble of GCM results would be fed through different hydrologic models to extend the range of climate scenarios to an envelope of recharge conditions.

4. Summary

This synopsis identified six recent publications that review the state of climate change and groundwater, and prediction of future recharge conditions. The reviews have several common conclusions. The uncertainty in GCMs and downscaling method, which govern the distribution and trend in future precipitation leads to widely varying results for predicted recharge. Often, recharge studies are not able to clearly indicate the magnitude and direction (increase or decrease) of future groundwater recharge because the GCMs themselves do not agree. Based on the articles reviewed, the influence on prediction of future recharge conditions seems to be, from greatest to least: (i) choice of GCM; (ii) choice of downscaling method; (iii) choice of recharge model; and (iv) choice of emissions scenario. Most researchers note that representing land surface – deep subsurface exchanges and groundwater flow directly into the GCM modelling process would help. However, communicating uncertainty and opposing results from multiple models will remain a challenge. Use of multiple models (GCM and hydrologic) that generate an envelope of results, and use of probability distributions appears to help close this gap.

The reviews also indicated that the most sensitive regions will be mountains (e.g. Engdahl and Maxwell, 2015) and arid zones (e.g. Gurdak and Roe, 2010; Shanafield and Cook, 2014), where subtle shifts in the timing and duration of seasonal weather will change recharge significantly. While arid regions were not considered explicitly in this synopsis, there has been a lot of effort directed toward understanding recharge in arid regions (Scanlon et al., 2006). Much remains to be learned from arid regions, as they preserve evidence of historic climate variability in their thick unsaturated zones.

Given that there is large uncertainty with modelling future recharge, the focus for managing water and aiding management decisions should be placed on the next 10–20 years rather than the next 50–100 years as is often done when modelling recharge. In this time horizon, much more will be learned about the impact of a changing climate through experience and observation, so long as observations are collected as noted by many researchers. Also in this time horizon, land use and soil properties may be similar to the present day. Certainly, longer time horizons are important to consider as well, but is must be acknowledged that land use and soil conditions could change (Holman, 2006) as humans adapt to a changing climate.

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