Journal of Hydrology 492 (2013) 244–253

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

# The uncertainty associated with estimating future groundwater recharge: A summary of recent research and an example from a small unconfined aquifer in a northern humid-continental climate

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ARTICLE INFO

*Article history:*
Received 1 November 2012
Received in revised form 13 March 2013
Accepted 30 March 2013
Available online 9 April 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ana P. Barros, Associate Editor

*Keywords:*
Groundwater recharge
Climate change
Climate scenarios
Downscaling
Snowmelt
Uncertainty

## SUMMARY

Global climate models (GCMs) project significant changes to regional and globally-averaged precipitation and air temperature, and these changes will likely have an associated impact on groundwater recharge. A common approach in recent climate change-impact studies is to employ multiple downscaled climate change scenarios to drive a hydrological model and project an envelope of recharge possibilities. However, each step in this process introduces variability into the hydrological results, which translates to uncertainty in the future state of groundwater resources. In this contribution, seven downscaled future climate scenarios for a northern humid-continental climate in eastern Canada were generated from selected combinations of GCMs, emission scenarios, and downscaling approaches. Meteorological data from the climate scenarios and field data from a small unconfined aquifer were used to estimate groundwater recharge with the soil water balance model HELP3. HELP3 simulations for the period 2046–2065 indicated that projected recharge was most sensitive to the selected downscaling/debiasing algorithm and GCM. Projected changes in average annual recharge varied from an increase of 58% to a decrease of 6% relative to the 1961–2000 reference period. Such a large range in projected recharge provides very little useful information regarding the future state of groundwater resources. Additional results from recent comparable studies are compiled and discussed. Based on the results obtained from the present case study and the other studies reviewed, the limitations of current approaches for projecting future recharge are identified, and several suggestions for research opportunities to advance this field are offered.

## 1. Introduction

Climate change has resulted in increases in globally-averaged mean annual air temperature and variations in regional precipitation, and these changes are expected to continue and intensify in the future (Solomon et al., 2007). Projected climate data are generated by simulating global atmospheric, oceanic, and surficial processes in global climate models (GCMs), which are driven by emission scenarios that require forecasts of future population growth and technology (Nakicenovic and Swart, 2000). GCM simulations are performed using coarse computational grids, and the results should be downscaled to produce local climate conditions that may subsequently be used for hydrology applications (Wilby and Wigley, 1997; Wilby et al., 2000).

The impact of climate change on the quantity and quality of groundwater resources is of global importance because 1.5 to 3 billion people rely on groundwater as a drinking water source (Kundzewicz and Döll, 2009). Despite the importance of the relationship between climate conditions and groundwater reserves (Taylor et al., 2012), research examining the effects of future climate change on groundwater has lagged corresponding research for surface water resources (Green et al., 2011). The IPCC Fourth Assessment Report stated 'knowledge of current [groundwater] recharge and levels in both developed and developing countries is poor. There has been very little research on the impact of climate change on groundwater' (Kundzewicz et al., 2007). This statement spurred an initiative to fill this research void, and a number of studies have emerged in the past 5 years that address the relationship between climate change and groundwater recharge (e.g., Aguilera and Murillo, 2009; Ali et al., 2012; Allen et al., 2010; Crosbie et al., 2010, 2011a,b, 2013, 2012; Dams et al., 2012; Döll, 2009; Ficklin et al., 2010; Green et al., 2011; Herrera-Pantoja and Hiscock, 2008; Holman et al., 2009; Jackson et al., 2011; Jyrkama and Sykes, 2007; Leterme et al., 2012; Liggett and Allen, 2010; McCallum et al., 2010; Mileham et al., 2009; Serrat-Capdevila et al., 2007;

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0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.03.043

Taylor et al., 2012; Thampi and Raneesh, 2012; Toews and Allen, 2009b; Wegehenkel and Kersebaum, 2009).

Recently there has been a discernible shift in the approaches used to examine climate change impacts on groundwater recharge. Rather than simulating changes for a single climate scenario, researchers have been employing multiple climate change scenarios generated from a variety of methods to produce a range, or envelope, of projected changes in recharge. Holman et al. (2012) suggested that the best practice for using climate model projections to assess the impact on groundwater was to 'use climate scenarios from multiple GCM or RCMs [regional climate models] …use multiple emission scenarios…[and] consider the implications of the choice of the downscaling method'. This approach introduces additional variability in the climate data, which translates into uncertainty in future groundwater recharge. For example, when more than 10 GCMs were employed for projecting future precipitation, it was found that less than 80% of the GCMs agreed 'in whether annual precipitation will increase or decrease' in most regions other than at high northern latitudes and in the Mediterranean region (Döll, 2009). The majority of uncertainty in the projected climate data (and consequently in the projected recharge) appears to stem from the selection of the GCM (Kay et al., 2009), although other factors, such as the emission scenarios, downscaling methods, or the hydrological model, can also contribute uncertainty (Crosbie et al., 2011a; Holman et al., 2009; Rowell, 2006).

Several recent groundwater recharge studies, employing multiple climate change scenarios, have been conducted at a very large scale. Döll (2009) simulated the vulnerability of groundwater to climatic change at the global scale using the hydrology model WaterGAP driven by climate data from two GCMs and two emission scenarios, and concluded that the uncertainty in projected precipitation from the climate scenarios resulted in uncertainty in recharge estimates which was spatially heterogeneous (e.g., see Australia, Fig. 1, Döll, 2009). Crosbie et al. (2013) simulated the changes in recharge for a 2050 climate for the entire continent of Australia using climate data from 16 GCMs and three emission scenarios to drive the WAVES hydrological model. Their study indicated that the range of projected changes in recharge was large and spatially variable and that it was generally difficult to project the magnitude or even direction of future recharge changes, although in certain regions of southern Australia, all 48 climate variants projected a decrease in recharge.

Many more regional scale studies have been conducted to investigate the link between climate change and groundwater recharge. For example, Serrat-Capdevila et al. (2007) used climate data for the San Pedro Basin from 17 GCMs to estimate recharge from a simple empirical equation. In the case of the drier climate projections, their simulations indicated that groundwater recharge could cease completely. Holman et al. (2009) simulated future groundwater recharge using one GCM, two emission scenarios, and two downscaling methods (a stochastic weather generator and the change factor method) and found that the uncertainty due to the downscaling method was greater than the uncertainty associated with the emission scenario. Allen et al. (2010) used climate data from four GCMs, one emission scenario, and one downscaling algorithm to drive simulations within a hydrology model of the Abbotsford-Sumas aquifer. Crosbie et al. (2011a) simulated groundwater recharge changes at three locations in southern Australia using multiple GCMs, downscaling methods, and hydrology models and found that the highest uncertainty in modeling future recharge arose from the selection of the GCM. Dams et al. (2012) used 28 climate scenarios to simulate a range of changes in mean annual recharge for a catchment in Belgium. Table 1 gives a summary of the results from these and other recent regional, continental, and global groundwater recharge studies.

The purpose of this contribution is to provide a case study that adds to the recent body of literature by examining the uncertainty in projected recharge for a humid-continental climate in which snow accumulation and melt are important factors affecting groundwater recharge. Seven climate scenarios generated from multiple (1) GCMs, (2) emission scenarios, and (3) downscaling/debiasing methods were utilized to drive simulations of future (2046–2065) groundwater recharge for a small, shallow, unconfined aquifer in central New Brunswick, Canada. Others (e.g., Jackson et al., 2011; Serrat-Capdevila et al., 2007) have examined the uncertainty in groundwater recharge due to varying one or two of the climate modeling options noted above, but this is the first contribution to examine the effect of varying all three following the recommendations of Holman et al. (2012). The uncertainty in recharge projections obtained in this study is also compared to the uncertainties reported in several recent groundwater recharge studies. Recommendations for future research opportunities are suggested based on the results obtained from the present case study and the studies summarized in Table 1.

**Table 1**
An overview of several recent studies that have employed multiple climate change scenarios to examine the impact of projected climate change on groundwater recharge.

| Study reference scenario | Number of GCMs | Number of ES[a] | Number of DM[b] | Scale of studies | Max changes in avg. recharge (%)[c] |
|---|---|---|---|---|---|
| Serrat-Capdevila et al. (2007) | 17 | 4 | 1 | Regional | −100 to ∼+35 |
| Döll (2009) | 2 | 2 | NA | Global | ∼−30 to +100[d] |
| Holman et al. (2009) | 1 | 2 | 2 | Regional | −14 to −37[g] |
| Allen et al. (2010) | 4 | 1 | 1 | Regional | −1.5 to +23[h] |
| Crosbie et al. (2010) | 15 | 3 | 1 | Regional | <−50 to >+50 |
| Crosbie et al. (2011a) | 5 | 1 | 3 | Regional | −83 to +447 |
| Jackson et al. (2011) | 13 | 1 | 1 | Regional | −26 to +31 |
| Crosbie et al. (2013) | 16 | 3 | 1 | Continental | +45 to +283[e] |
| Dams et al. (2012) | 5 | 2 | 1 | Regional | −20 to +7 |
| Ali et al. (2012) | 15 | 3 | 1 | Regional | −33 to +28[f] |

[a] ES = emission scenarios (A1F1, A2, A1B, B1, etc.).

[b] DM = downscaling methods.

[c] For studies with multiple locations, this column lists the results from the locations with the highest uncertainty in the mean annual recharge estimations.

[d] Estimated from the southwestern Australian region in Fig. 1 of Döll (2009).

[e] Taken from Appendix C of Crosbie et al. (2011b), these results were for Brunswick Coastal Sands for the median dry climate and the median wet climate.

[f] Taken from Table A1 of Ali et al. (2012), these results were from the Southern Perth Basin for the wet and dry simulations compared to the recent recharge.

[g] Taken from Table 1 of Holman et al. (2009) for loamy soil and the 2050's climate scenarios.

[h] Allen et al. (2010) have a discrepancy between the reported recharge ranges in their abstract (−10.5% to +23.2%) and in their Fig. 13 (−1.5% to +23.2%). The text in the results seems to suggest that the latter is correct.