
Journal of
Water and Climate Change

Potential impacts of climate change on groundwater resources – a global review

Sam Earman and Michael Dettinger

ABSTRACT

Groundwater is a vital resource for sustaining life. Changes in the Earth's climate have the potential to affect both the quality and quantity of available groundwater, primarily through impacts on recharge, evapotranspiration and (indirectly) on pumpage and abstraction. Groundwater is a major contributor to streamflow in areas with relatively shallow water tables, so changes in groundwater systems may also impact surface-water systems. As a result, understanding how climate change could affect groundwater systems is a vital component of sound long-term management of our water supplies. However, predicting how climate change could impact groundwater systems is difficult. Part of the difficulty is rooted in uncertainties in the predictions of future climate. However, even if we were certain regarding future climate, forecasting future groundwater conditions would still be difficult because of the complex combinations of processes that affect groundwater recharge, discharge and quality. Better observations, increased understanding of processes and modeling capabilities will be needed to assess the future of this vital resource in the face of projected climate changes.

Key words | climate change, evapotranspiration, groundwater, monitoring modeling, pumpage, recharge, streamflow, water quality

Sam Earman (corresponding author)
Earth Sciences Department,
Millersville University,
Millersville, PA 17551,
USA
E-mail: *searman@millersville.edu*

Michael Dettinger
US Geological Survey,
La Jolla, CA 92093
USA

BACKGROUND

Groundwater is a vital resource for sustaining life. Groundwater is the Earth's largest reservoir of fresh, liquid water, accounting for nearly 70 times more water than is present as surface water (Fetter 2001), and it accounts for approximately 20% of total water use worldwide (Zektser & Everett 2004). Groundwater supplies 21% of total water use in the USA (Hutson *et al*. 2004) and more than 70% of consumption in most European nations (Zektser & Everett 2004). In many parts of the developing world, where surface water is either scarce or contaminated, groundwater is vital for sustaining human life. Some major metropolitan areas, such as Las Vegas, NV (USA), that have recently relied primarily on surface-water supplies are turning towards groundwater to cope with combinations of population growth and less-certain surface-water supplies (Eckstein & Eckstein 2003).

Groundwater is also a major contributor to stream and river flows, especially in areas with shallow water tables, during both low-flow periods and high flows (Genereux & Hooper 1998). As a result, the status of groundwater systems not only impacts their usefulness as water-supply sources but also may impact the availability of surface-water supplies. Furthermore, groundwater systems and the surface-water systems that depend on them play important roles in many ecosystems. For example, groundwater inflows to many wetlands are crucial to the health, abundance and diversity of species.

Changes in Earth's climate have the potential to affect both the quality and quantity of groundwater. Scientific consensus holds that the Earth's climate has been changing, and that change will continue in the future, in response to increasing greenhouse-gas concentrations in the global atmosphere. Current models of climate change over the next ~50 years are unanimous in projecting that air temperatures will rise. Most projections involve increases of 3–5 °C on global average, with warming in all parts of the world, but with more

doi: 10.2166/wcc.2011.034

warming projected in polar regions and less in the tropics (Intergovernmental Panel on Climate Change 2007). Projections of future precipitation are not as unanimous or certain, but generally yield drier dry areas and wetter wet areas (Intergovernmental Panel on Climate Change 2007). Predictions of future rates of evaporation and transpiration (water use by plants) are also relatively uncertain, although historically evapotranspiration (ET, the combination of evaporation and transpiration) has tended to vary less than precipitation in most settings. General warming, in combination with uncertain precipitation changes, is expected to yield less fresh water availability in most settings than would occur in response to the precipitation changes alone. That is, even if precipitation remains constant (or increases marginally), under warming conditions less runoff and recharge will likely result. Where precipitation declines, warming will likely magnify the resulting runoff and recharge reductions. Increasing carbon dioxide concentrations in the atmosphere may produce fertilization effects that could change the transpiration efficiencies of plants, potentially decreasing water demands and effectively restoring some of the water availability for runoff and recharge lost to warming conditions (Betts *et al*. 2007). However, consensus on the net effect of carbon dioxide fertilization effects remains elusive (e.g. Cruz *et al*. 2010).

This review will discuss some of the ways in which groundwater systems might be vulnerable to projected climate changes. The literature regarding interactions between climate and groundwater is not as extensive as that dealing with surface water. Because groundwater systems often store much larger volumes of water than do surface-water systems, and because groundwater systems are often the primary supply options when others fail during droughts, an implicit assumption that groundwater supplies are less vulnerable to climate and climate change than are surface waters underlies many models and studies (Dettinger & Earman 2007). Consequently, thus far, studies and models of climate change impacts on hydrologic systems have tended to focus on surface water systems (McCarthy *et al*. 2001). In many cases, studies of climate change impacts on surface-water systems make little or no mention of groundwater, and do not appear to make a realistic accounting of groundwater contributions to streamflows. In part, this approach has proceeded from observations that climatic influences on surface water are commonly more rapid than influences on groundwater, thus driving assumptions that climate-change influences on groundwater are less pressing.

However, the potential for changes in the water balances of small aquifers and shallow mountain aquifers, the potential for immediate influences on surface-water supplies and the potential for long- and short-term influences on groundwater quality should all motivate more attention to potential interactions between climate change and groundwater. What has limited such understanding in the past has been a long history of groundwater concepts and models that underplay climatic influences and a lack of the observations needed to fuel improvements in models and understanding. We hope that this review will serve to draw greater attention to the vulnerabilities of groundwater quantities and qualities, and their contributions to surface waters and even ocean waters, in the face of projected climate changes. This review will survey potential impacts of climate change on groundwater quantity, on groundwater – surface-water interactions and on groundwater quality, in turn. Then some of the modeling and monitoring needs that must be addressed to accommodate possible climate-change influences will be reviewed.

POTENTIAL IMPACTS OF CLIMATE CHANGE ON GROUNDWATER QUANTITY

Overview and theoretical concepts

Projections of climate-change impacts on groundwater systems are inherently uncertain because estimates of future climate are uncertain. An additional source of uncertainty is that the interactions of climate with groundwater are generally poorly understood and modeled. Some climate-change impacts are likely to be direct responses to changes in temperature, precipitation and increased CO_2 concentrations. Other impacts on groundwater systems will be indirect, arising from changes in land use, in availability of other (surface) water supplies, in human water demands, in the areal distribution of native and farmed plant communities, and/or changes in the water consumption of current crops and native plants in response to climate and carbon dioxide concentrations. Land use and vegetation types affect groundwater systems significantly because they exert controls over both the infiltration of precipitation or irrigation waters into the ground and the extraction of that water from unsaturated zones before it has a chance to become groundwater recharge (Eckhardt & Ulbrich 2003; Scanlon *et al*. 2005, 2007; Thomson *et al*. 2005; Green *et al*. 2007). At present, even the responses of groundwater resources to short-term (year-to-year, decade-to-decade) climate variability are poorly monitored, understood, and quantified.

We consider here four broad avenues by which climate change may affect groundwater systems: changes in precipitation amounts, changes in the temporal distribution of precipitation; changes in the form of precipitation (rain vs. snow) and changes in evaporation, transpiration and, indirectly, groundwater pumpage rates (Figure 1). Changes in precipitation may directly impact recharge to groundwater systems, while changes in several other climatic variables (Figure 1) may, separately or together, impact the various mechanisms of groundwater (and soil moisture) discharge. Because climate change may potentially yield disparate impacts on the environment, there are a number of other, mostly indirect, ways that groundwater may be impacted. For instance, a warming climate may lead to increased frequency of forest fires (Westerling *et al*. 2006), which can change groundwater recharge in the burned areas by changing soil permeability and overland runoff. Land-use change, whether associated with climate change or not, is likely to result in changes to infiltration and thus groundwater recharge.

Changes in precipitation amounts, ET and pumpage

The most basic continuity expression for groundwater systems is that the mass of water input to a system minus the mass of water removed from the system is equal to the change in mass of the water stored in the system. An increase in total precipitation at any given location increases the amount of water that is available to become groundwater recharge and, in the absence of other influences, may drive increased recharge. Conversely, less precipitation is expected to result in less recharge. Changes in ET driven by any of several potential climate changes can affect the amount of groundwater recharge by changing the consumption of water at the land surface, from the unsaturated zone, and – in the case of phreatophytes (plants that obtain a significant part of their water from the saturated zone) – from below the water table. Many studies support the intuitive concept that changes in the rates of precipitation and/or ET would lead to changes, of the same sign,

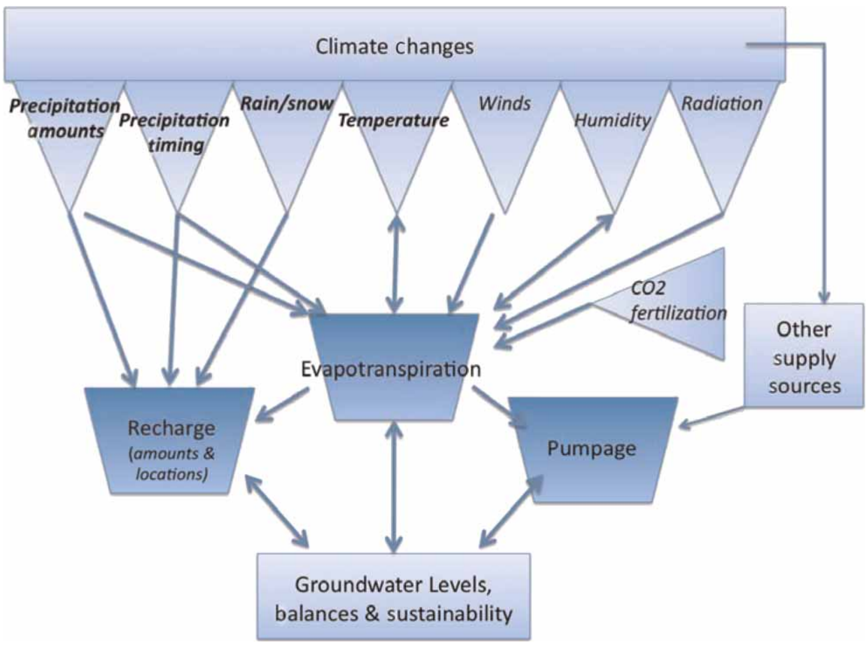

Figure 1 | Conceptual diagram illustrating relationships between climate factors and recharge. This diagram is meant to suggest some major factors and relationships and is not intended to be a complete or exhaustive representation.

in groundwater recharge (e.g. Sandström 1995; Tanco & Kruse 2001; Fleming & Quilty 2006).

ET rates reflect energy balances at the surface and water availability at the surface and in root zones. The surface-energy fluxes that are most important for ET typically include net radiation at the surface and the evaporative (latent heat) fluxes from the surface and root zones. Surface latent heat fluxes depend on the partitioning of surface heat imbalances between sensible and latent heat fluxes, as indexed by the Bowen ratio (Dow & DeWalle 2000). Most climate-change impact assessments published to date have focused on changes in precipitation and air temperatures while changes in other variables, such as solar radiation fluxes (and cloudiness), longwave radiation fluxes, surface winds, and humidity (Figure 1), may contribute equally to changes in evaporative demands and actual ET rates.

Although CO_2-induced changes in temperature have been the most frequently invoked driver of changes in transpiration rates in climate-change impact assessments, the rising CO_2 concentrations themselves may directly impact transpiration rates (Bazzaz & Sombroek 1996). Changes in atmospheric CO_2 concentrations can cause a number of changes in plants, often termed 'CO_2 fertilization', including increased leaf area index (the ratio of leaf area to soil surface area), changes in the density of stomata (the pores through which plants exchange gases with the atmosphere) and changes in stomatal opening and closing (Bazzaz & Sombroek 1996). There are three mechanisms by which plants photosynthesize, known as the C3, C4 and Crassulacean acid metabolism (CAM) processes (Sternberg & Deniro 1983). Because different plant species use these different photosynthesis processes (e.g. wheat uses the C3 process, corn uses the C4 process, and pineapple uses the CAM process), different plant species are likely to respond differently to changes in atmospheric CO_2 concentration (Ward *et al.* 1999). It is possible that, in some regions, increased CO_2 may change transpiration demand enough (Figure 1) to at least partially offset decreased precipitation, or enough to greatly increase recharge in wetter locales (Green *et al.* 2007). For instance, detailed modeling of subtropical soil–water–vegetation systems indicated that CO_2 fertilization, together with a ~40% increase in precipitation, might increase groundwater recharge by as much as 500% in some settings (Green *et al.* 2007).

In many parts of the world, groundwater is pumped from aquifers for human uses, including domestic supply, irrigation and industrial applications. Changes in temperature or precipitation may ultimately lead to changes in water demand. For instance, in Calgary, Alberta (Canada), historical urban water demands (mostly for domestic outdoor and indoor uses) have been fairly constant when precipitation is at or above average and temperatures are low. However, when temperatures have risen above 10 °C or when precipitation declines to less than about 20 mm/week, historical demands for water increased exponentially with the changes in climate (Akuoko-Asibey *et al.* 1993). Thus changes in climate may be expected to affect the timing and amounts of demand for water. If climate change causes human demands for water to increase and if surface-water supplies are either not available or not adequate to meet increasing demands, groundwater pumpage may be expected to increase. In addition to directly removing water from storage, increased pumping could reduce the storage capacity of the aquifer and affect hydraulic conductivity if the additional pumping causes or accelerates aquifer compaction; structural damage resulting from land subsidence could also be a consequence (Freeze & Cherry 1979).

Changes in timing of precipitation

Changes in the timing of precipitation on scales from hours to years also have the potential to affect groundwater recharge (Figure 1). In general, for recharge to occur, enough water must infiltrate the unsaturated zone to overcome evapotranspirative and tensive demands between land surface and water table (Flint *et al.* 2004). In many settings, a single storm may not provide enough water to overcome these demands, but that demand threshold might be exceeded by the amounts of water accumulated from several storms. However, if a long dry period elapses between the storms, much of the water from the first storm might already be extracted from the unsaturated zone as ET before the second storm occurs. Because of such requirements on both precipitation amounts and timing, changes in the distributions of arrival times of storms or lengths of interstorm periods are likely to affect recharge rates. Shifts of precipitation into warmer seasons with higher evaporative demands, or tendencies towards

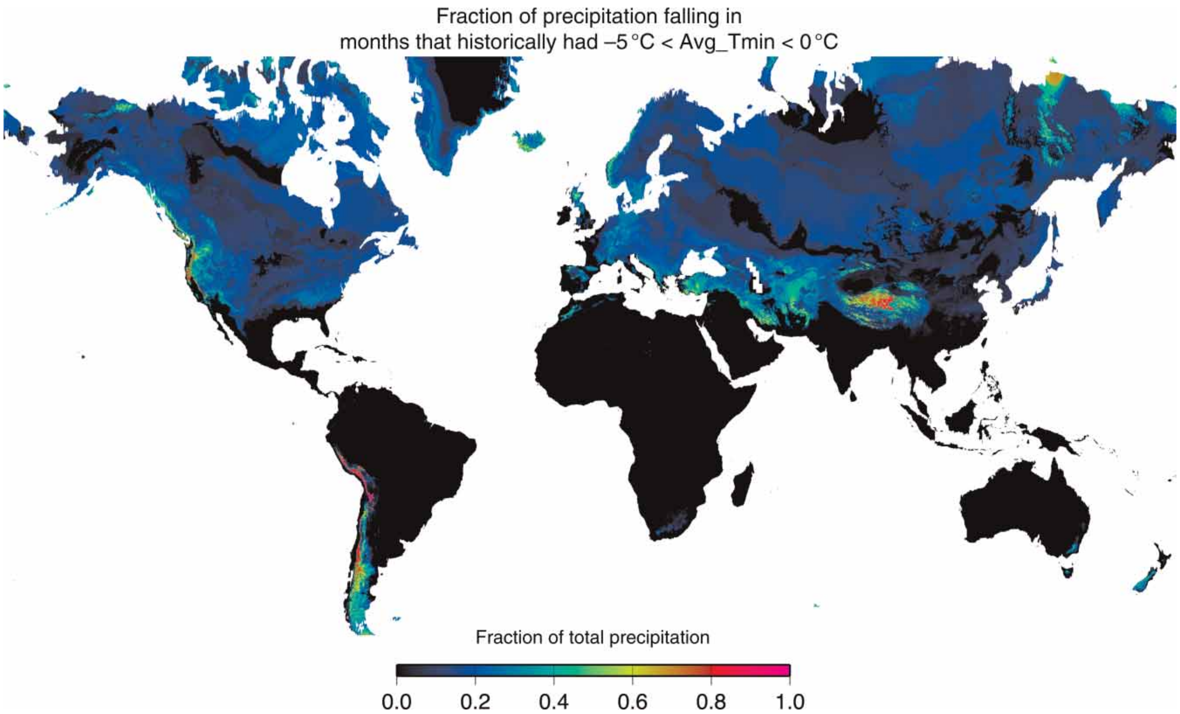

Figure 2 | Fractions of long-term average precipitation totals that historically fell during months with average daily minimum temperatures between −5 °C and 0 °C, based on the WorldClim 5-arcminute interpolated climatological (1,950–2,000 means) precipitation and temperatures data set (Hijmans *et al*. 2005; www.worldclim.org).

more frequent or drier drought years, could similarly affect recharge rates.

An example of this phenomenon has been observed in Barbados, where groundwater recharge is more dependent on the timing of precipitation than on the total amount of precipitation in a year (Jones & Banner 2003). In that setting, years in which precipitation was largely limited to the monsoon season tended to yield more recharge than years when precipitation was more evenly distributed throughout the year, even if total precipitation amounts were similar (Jones & Banner 2003). In this kind of system, a climate change favoring more storms or a more-even seasonal distribution of storms could reduce groundwater recharge, while a change towards higher fractions of annual precipitation during a single season could increase recharge.

Changes in the form of precipitation

In snow-dominated regions, the seasonal timing (and, thus, form) of precipitation may also be important. Precipitation type is important because snowmelt can contribute disproportionately high percentages of groundwater recharge in snow-dominated regions (Earman *et al*. 2006). In this section, we will focus on the western USA as an example because more research is currently available from that region, but the findings and concepts are likely to apply in other parts of the world (Figure 2) where snowpacks are significant (Barnett *et al*. 2005).

In the semi-arid western USA, snowmelt is a much more likely source of groundwater recharge than is rain (Simpson *et al*. 1972; Winograd *et al*. 1998; Earman *et al*. 2006). Because evapotranspirative potential in the western USA is high, the amount of water in individual rain events is often insufficient to produce recharge. Snowmelt has several advantages over rain with respect to generating recharge. Snowpacks form large reservoirs of water during the winter months that are then available for prolonged infiltration during the local snowmelt season. Because snowpacks generally contain water from a number of storms, the sustained snowmelt in the spring typically yields significantly more water than any single storm and is much more likely to become recharge. Snowmelt is also typically a fairly gentle process, yielding relatively steady flows of water that are available to percolate downward, in contrast to summer rains in the West, which are often intense events that yield more overland runoff and less infiltration. Snowmelt generally occurs when temperatures are still locally cool and vegetation is relatively inactive, and thus when transpiration demand is relatively low. In addition to the low transpiration demands, snowpack's high albedo (reflectivity) prevents significant fractions of solar energy from being absorbed at the land surface, resulting in much lower evaporative demands than would occur if no snowpack were present.

In the western USA, warming temperatures over the last ~50 years have already caused declines in snowpack accumulations (Mote 2003; Mote *et al*. 2005) and trends that favor rainfall over snowfall (Mote 2003; Mote *et al*. 2005; Knowles *et al*. 2006). Continued warming is expected to further decrease the amounts of snow that fall, even if precipitation volumes do not change significantly. Because snow-to-rain shifts replace a more efficient recharge agent (snowmelt) with a less efficient recharge agent (rainfall), such shifts have the potential to drive declines in the efficiency of groundwater recharge in snow-dominated areas. With additional warming, ET is generally expected to increase, so overall outflows of water, including recharge, may be expected to decline in many settings while also making the unsaturated-zone barrier to recharge even steeper. However, whether these increased potentials for ET will directly sap the outflows most crucial to recharge remains uncertain because the greatest increases in evaporative demands will likely be in the warm season, while most (snowfed) recharge probably happens in the spring season before the warmest temperatures of summer.

Globally, a number of mountainous regions receive large parts of their precipitation as snow (Barnett *et al*. 2005). Where large fractions of that snowfall occur at temperatures near and below freezing, modest warming may yield large changes in precipitation form that, in turn, may affect recharge totals. Such regions may be more susceptible to early effects of global-scale warming because only minor warming would be necessary to yield storms that historically might have been mostly below freezing (allowing snow to fall) but that now might be mostly above freezing (making rain more likely to fall). Such areas have been mapped at reconnaissance levels in North America by Dettinger & Culberson (2008) (see also Bales *et al*. 2006) using gridded daily historical temperatures and precipitation data from Maurer *et al*. (2002). The delineations of these regions has been confirmed over North America, with the same data sets and analyses as in the global analysis that follows, using monthly precipitation and temperature fields from the PRISM gridded climate data sets (Daly *et al*. 1994 and updates thereto). A global reconnaissance analysis to identify regions that might be most susceptible to snow-to-rain transitions of significant fractions of overall precipitation with a hypothetical uniform +5 °C warming is shown in Figure 2. Regions with the largest fractions of historical precipitation in the vulnerable temperature range (shaded with the warmest colors in Figure 2) include broad areas around the Himalayan Plateau, the Sierra Nevada and Cascade Range of the western USA, the central and southern Andes of South America, the South Island of New Zealand, Patagonia, and mountainous regions of Turkey, Iran and Afghanistan. These are regions in which historically snowmelt-fed groundwater recharge may be most vulnerable to warming trends in the 21st century.

However, even under these circumstances, it is not certain that total recharge will decline. In the western USA, most snow falls in mountainous areas, and water that does not recharge the mountain aquifers beneath the snowfields can run into adjacent basins, where seepage from streambeds can be an important recharge mechanism. If the 'in-place' recharge beneath the snowfield in the mountains declines due to a snow-to-rain shift, some of the water not recharged might instead become increased streamflow out of the mountains and onto adjacent basins. Under these circumstances, recharge through streambeds in basins might be increased. In such a scenario, although mountain recharge might decline and the recharge locations change, the recharge totals (to the combination of mountain *and* basin aquifers) might not change or might change in ways that are difficult to predict. Alternatively, in many mountain settings, water not recharged may remain in thick unsaturated zones until it is evaporated or transpired at some later date, which would result in overall recharge declines.

General considerations

The vulnerability of specific groundwater systems to these various climatic influences will depend on non climatic factors. Less extensive, volumetrically smaller aquifers may show climate-change influences more quickly than larger aquifers. Aquifers in arid to semi-arid settings may be more vulnerable to changes than aquifers in more humid environs. As indicated, snowfed aquifers may be more prone to warming influences than other aquifers.

There is no single answer to the question of how climate change will influence groundwater flow systems. Different systems, and even different components and locations within a single groundwater system, will respond to climate changes in distinct ways. As a consequence, more observation and research into the historical linkages between climate and groundwater hydrology, in many different settings, is needed. No single groundwater model is likely to be well suited for all geographic and hydrologic settings, and consequently a variety of modeling and predictive approaches may be needed to synthesize the observations and research into actionable predictions of climate-change impacts on groundwater systems.

IMPACTS OF GROUNDWATER CHANGE ON SURFACE WATER

Contributions of groundwater to surface-water flows may prove to be among the most vulnerable to climate change in many settings. It is widely recognized that stream baseflow (the water still flowing in a stream during the low-flow period of the year) results from groundwater inflows to the stream channel (Viessman *et al*. 1989). Less well known thus far, though, is the fact that studies using chemical and/or isotopic hydrograph separation methods have shown that, in many systems, groundwater inflow is a major contributor (on the order of 25–75%) to streamflow even during peak flow periods like storms and snowmelt seasons (Genereux & Hooper 1998). Major contributions of groundwater to peak flows occur even in mountain catchments composed of crystalline rock (Genereux & Hooper 1998; Soulsby *et al*. 2007), although such drainages have often been assumed to be impermeable in streamflow models.

Because of the nonlinear nature of groundwater-stream interactions, the impact of changes in groundwater systems on streamflow is rarely a simple 1:1 relationship (Figure 3). Most streams that receive groundwater inflow are shallow compared to the thickness of the aquifers that supply the inflow. As a result, streams typically receive their inflows only from the uppermost parts of the contributing aquifers. When declines in groundwater recharge or storage cause water tables to drop, those declines most immediately affect the water table or uppermost limits of the aquifers, which are the parts of the aquifer that contribute to streamflow. As a result, relatively small reductions in recharge and groundwater storage, resulting in relatively modest declines in water-table altitudes, can translate into significant declines in groundwater contributions to streamflow. Conversely, increased recharge can lead rapidly to increased streamflows.

An example of the disproportionate relationship between changes in groundwater storage and resulting changes in streamflow comes from the Republican River basin in the central Great Plains of Kansas and Nebraska (USA). By comparing flows in that basin from 1950–1964 with those in 1986–2000, Knox (2006) has shown that declines in groundwater storage (caused primarily by pumping for irrigation) of about 3–5% (Alley 2007) have led to declines in stream baseflow of approximately 31% and declines in total streamflow of approximately 35%. Monthly mean values for precipitation and temperature in southwestern Nebraska (a major part of the Republican River basin) during the two periods considered showed no significant difference (using Kruskal–Wallis tests), verifying that differences in temperature and/or precipitation were not responsible for the decline in streamflow.

In terms of overall water supplies, declines in streamflow due to climate change (Figure 4) may force changes in reservoir management that might, in turn, affect the amounts of water supplied for direct consumption or irrigation. Such changes in surface-water supplies may result in more pumpage and reliance on groundwater supplies. In settings where mountain recharge declines as a result of being effectively shunted into streams flowing from mountains (e.g. the previous section), the additional streamflow is likely to occur during the seasons (and intervals) when water is already plentiful. As a result, such streams may become more prone to brief, high peak flows, than they were under the historically moderating influences of groundwater inflow. Where surface-water storage is plentiful, this

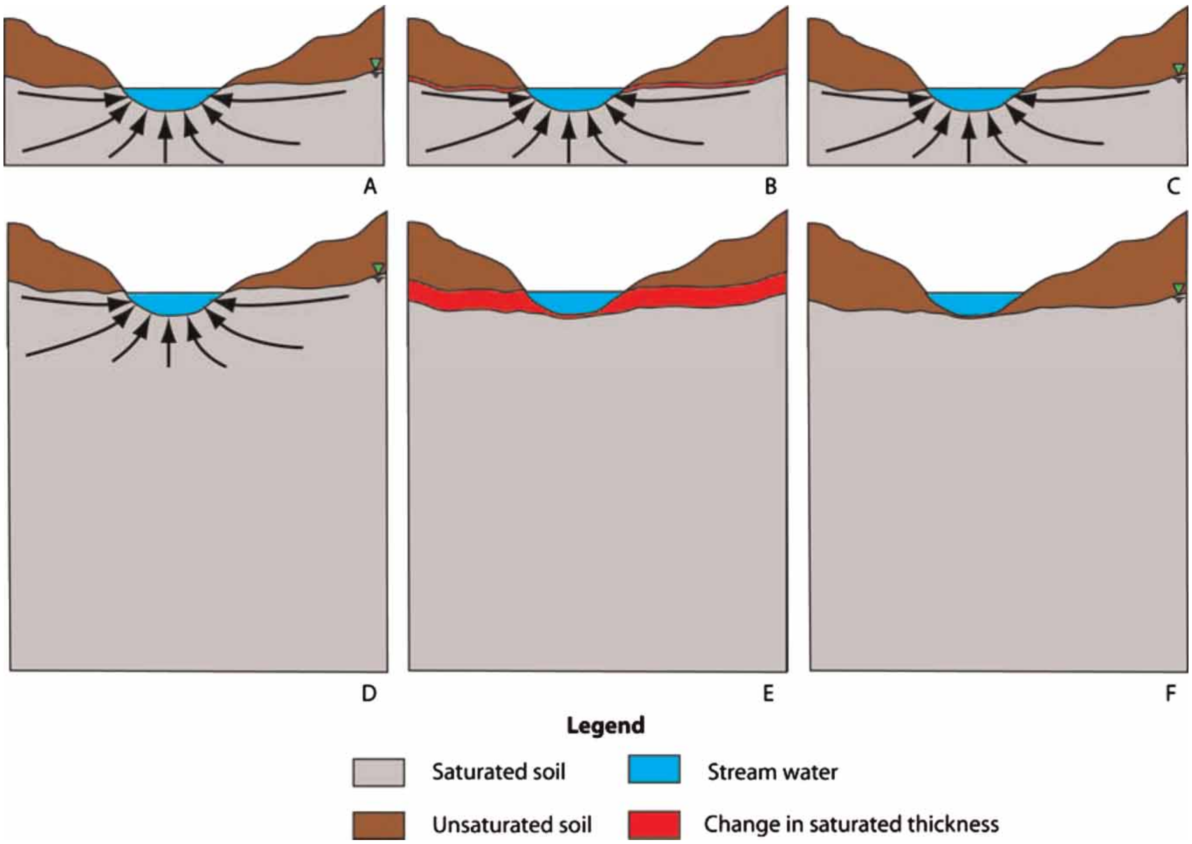

Figure 3 | When groundwater contributes to streamflow, the relationship between change in aquifer storage and inflow to the stream is not necessarily straightforward. Aquifers that contribute to streams are often shown in conceptual diagrams as being only moderately thicker than the stream depth (A). In such a system, a change in aquifer storage may yield a change in the groundwater contribution to streamflow of similar proportion (e.g. a 10% decrease in groundwater storage would lead to a change in groundwater contribution to a streamflow of ~10%). If the 'textbook' (thin relative to stream thickness) aquifer shown in (A) had its saturated thickness reduced by 5% (B), the aquifer could still contribute a significant amount of water to the stream (C). In reality, many aquifers that contribute to streamflow have saturated thicknesses far greater than the stream depth (D). In these systems, relatively small changes in groundwater storage can lead to relatively large changes in groundwater contribution to streamflow because the changes will be manifested in the uppermost portion of the aquifer, where the stream-aquifer interface is present. In this conceptual system, a decrease in saturated thickness of 5% (E) is enough to lower the water table below the streambed (F), causing a total loss of groundwater contribution to streamflow.

situation may not be too problematic but, in general, tendencies for briefer high flows would be expected to make management of surface-water supplies more difficult.

Finally, many ecosystems may be vulnerable to changes in the groundwater – surface-water relations that support them. Spring, wetland, riparian and estuary ecosystems are all quite responsive to natural fluctuations in flows to and through them, on time scales from hours to decades (e.g. Sada *et al*. 2001; Kimmerer 2002). If, in response to climate change, the partitioning of streamflow sources between faster, shorter duration surface-runoff sources and slower, longer duration groundwater-baseflow sources changes, the impacts on ecosystems may be profound.

CLIMATE CHANGE AND WATER QUALITY

Climate change may also impact groundwater quality. In addition, even if no changes in groundwater quality occurs under a changed climate, changes in the amounts of groundwater entering other water systems may change the quality of those receiving waters (Figure 4).

Because precipitation is chemically dilute, the majority of the dissolved material in most aquifers used for human water supplies derives from water-rock interactions in the subsurface. Mixing with high-salinity water from other sources and evaporative concentration of dilute waters are other mechanisms for increasing salinity. If climate change

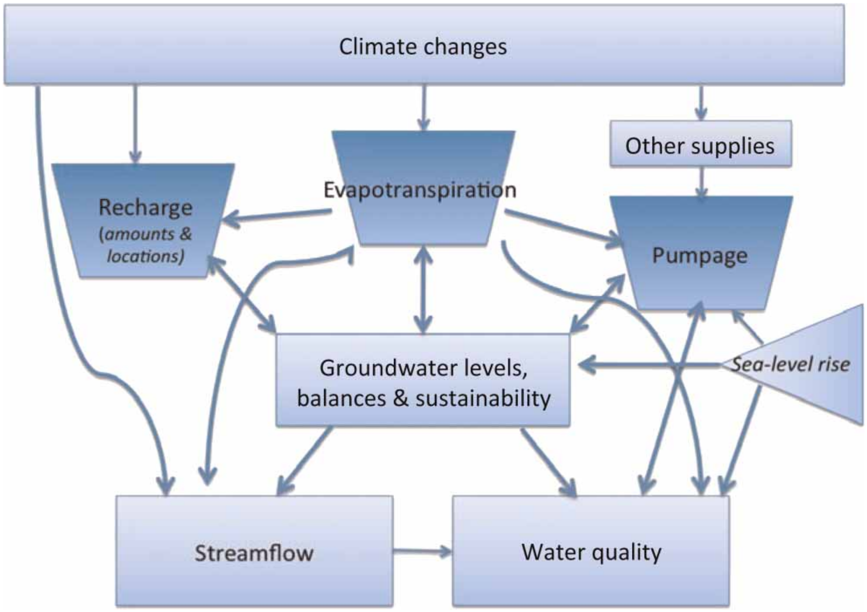

Figure 4 | Conceptual diagram illustrating major relationships between climate factors and various aspects of the water cycle.

alters the amount of time for, or the chemical conditions during, water-rock interaction, it could cause degradation in groundwater quality. Similarly, changes in the rates of evaporation or saline-water inflows into less-salty aquifers could also cause groundwater quality to suffer. Reduced hydraulic gradients resulting from reductions in groundwater recharge could lead to longer residence times in aquifers; increased residence time allows greater water-rock interaction and typically leads to increased levels of salinity (Hem 1992; Kayane 1997).

Because reduced recharge could lead to increased groundwater salinity, it might seem that increased recharge would necessarily yield higher-quality groundwater. However, increased recharge can also result in increased salinity, albeit for different reasons. Increased recharge could cause increased flushing of salts from the unsaturated zone (Sugita & Nakane 2007), which in turn might increase groundwater salinity. Of particular concern in this regard is nitrate, the consumption of which can cause methemoglobinemia. While nitrate is susceptible to increased leaching in many different climate zones (Sugita & Nakane 2007), nitrate leaching may prove to be especially problematic in arid areas where large reservoirs of nitrate accumulate in unsaturated zones by natural processes (Walvoord *et al.* 2003; Graham *et al.* 2008).

Declines in groundwater storage (and the associated falling groundwater levels) resulting from reductions in recharge and/or increases in pumpage would be expected to result in smaller groundwater contributions to streamflow. A common impact of decreased baseflow in streams is increased streamwater temperature, because groundwater in many settings is cooler than water than has traveled over land to (and through) stream channels. Warmer stream temperatures may have significant impacts on species viability (Coutant 1999; Wissmar *et al.* 1994). In contrast, where recharge increases, greater groundwater contributions to streams are unlikely to cause temperature stress among existing biota. Streamwater chemical quality may also be changed if groundwater contributions to streams change in response to climate, although the overall effect will depend on the relative qualities of groundwater and stream water.

Globally, sea levels have risen by about 22 cm in the 20th century. Sea levels are expected to continue to rise, probably increasingly rapidly, in response to global warming, as ocean waters warm and expand and major icesheets melt into the seas (Rahmstorf 2007). In coastal areas, these higher sea levels are likely to increase the potential for intrusion of ocean water into freshwater aquifers, thus threatening to increase groundwater salinity (Sherif & Singh 1999; Ranjan *et al.* 2006). Such sea-level-driven threats to groundwater salinity may either be exacerbated by climate-driven declines in recharge rates elsewhere in the basins, or ameliorated by increases in recharge. Even salinities in aquifers far removed from oceans may be affected by climate change if reductions in recharge or increases in pumpage of freshwater aquifers causes upwelling of saline water from surrounding formations (Chen *et al*. 2004).

Conversely, changes in groundwater quantity and quality also influence ocean chemistry, especially near coasts (Loaiciga 1999). Although the volume of groundwater discharge to the oceans is only about 6% of streamflow discharge into the oceans, groundwater's annual salt input to the oceans is about 30% of the amount contributed by streamflow (Loaiciga 1999). Changes in the quality of groundwater could thus alter near-coast ocean chemistry and nutrient cycling (Loaiciga 1999). Changes in sea level and groundwater levels could change the volume of groundwater discharging to the oceans by altering the magnitude and/or direction of the hydraulic gradient between aquifers and oceans.

PREDICTING CLIMATE-CHANGE IMPACTS ON GROUNDWATER SYSTEMS

Methods for prediction and associated strengths/weaknesses

The few available predictions of the impacts of climate change on groundwater systems have relied on numerical models, which are typically calibrated to historical data and then run using climate projections as input (e.g. Croley & Luukkonen 2003; Brouyère *et al*. 2004). In other cases, historical data are used in conjunction with climate records to determine how past changes in climate have affected groundwater systems (e.g. Chen *et al*. 2001; Piggott *et al*. 2001; Ferguson & St. George 2003; Gurdak *et al*. 2007; Person *et al*. 2007). Another approach involves adding spatially distributed information about water scarcity and degree of dependence on groundwater to a model of climate-recharge relations, yielding areal estimates of vulnerability to climate change impacts on groundwater systems (Döll 2009).

To parameterize future climate, some studies have imposed specific and, usually, uniform changes in temperature and precipitation to the groundwater-system models (e.g. Loáiciga 2003) so that, for example, historical temperatures are increased by 2 °C and precipitation by 10% for a given simulation experiment. Other studies use more temporally and spatially detailed downscaled climate simulations from general circulation models (GCMs) of climate responses to increasing greenhouse-gas concentrations in the atmosphere (e.g. Rosenberg *et al*. 1999; Thomson *et al*. 2005; Scibek & Allen 2006; Scibek *et al*. 2007). Although use of GCM-based climate projections appears more rigorous on the surface, imposed-change simulations can be designed to reflect mean annual changes from the same GCM outputs.

In addition, significant differences exist between climate-change scenarios derived from different GCMs, or from the same model's responses to the various possible scenarios of future greenhouse-gas emissions (e.g. Herrera-Pantoja & Hiscock 2008). Thus, the particular combination of GCM used and emissions scenario assumed has a major impact on the changes simulated by a groundwater model (Rosenberg *et al*. 1999; Malcom & Soulsby 2000; Croley & Luukkonen 2003). Consequently, impact studies (especially for surface-water systems) generally analyze impacts simulated from several GCMs and a range of emissions scenarios. One example of these issues is a study that used output from two GCMs to evaluate possible changes in groundwater recharge in Lansing, MI (USA). Using one GCM, a 20% decrease in recharge was predicted, but the results using the second GCM suggested recharge would increase by 4% (Croley & Luukkonen 2003). In studies of surface-water impacts, such differences are increasingly being accommodated by analyzing larger collections of climate-change projections in order to provide bases for identifying the responses that are most commonly suggested regardless of the climate-change projections used (e.g. Chiew *et al*. 2009). Such assessment strategies can provide groundwater managers with a better understanding of the full range of possibilities that they may face. Notably, though, among current GCMs, the contributions or feedbacks of groundwater systems into climate are only cursorily represented. Ideally, future generations of GCMs will be improved with better representations of the slowly evolving influences that groundwater systems and, especially, groundwater discharges may have on the surface hydrology and surface-energy fluxes that affect climates over land surfaces (Committee on Hydrologic Science 2004).

Even if GCM projections of future climate were unanimous and certain, major hurdles will still need to be overcome with regard to using climate projections to accurately estimate changes in groundwater systems. Current groundwater models typically estimate distributed (as opposed to stream-channel bottom) groundwater recharge as a specified, calibrated fraction of total precipitation (Anderson & Woessner 1992b), without regard for the myriad factors that can influence recharge. Accurate models of groundwater conditions under climate change will generally need to be run in transient mode, as the changing inputs and outputs will be the focus of most assessments. Specific yield of an aquifer can be difficult to quantify accurately, but it is a property that has a tremendous impact on transient aquifer responses to changing stresses (Howard & Griffith 2009). Indeed, little modeling or monitoring experience exists that could be used to dictate how the cascades of change that will be brought about by warming (e.g. changes in transpiration, changes in pumping because of increased water demand) will influence groundwater recharge in a simulation model.

Until very recently, groundwater models have typically been designed and run as standalone systems, uncoupled with surface phenomena. Thus, changes in groundwater recharge, flow and discharge have typically been modeled without much consideration of changing climatic or vadose zone conditions (Markstrom *et al.* 2008). The recent development of coupled groundwater – surface-water models (e.g. GSFLOW (Markstrom *et al.* 2008)) incorporating interactions between surface runoff, flow in the unsaturated zone, ET and groundwater offers avenues through which this weakness may be addressed.

Another difficulty in simulating climate-change impacts on groundwater systems is that GCMs and groundwater models tend to operate on significantly different spatial and temporal scales (Hanson & Dettinger 2005). As a result of all of these issues, coupling GCMs and groundwater models remains difficult and largely experimental.

Given the fact that the relations between climate and groundwater recharge are poorly understood (Heppner *et al.* 2007), there is significant potential for groundwater models, which typically are based on small, short-term data sets, to yield misleading results. Post-audits of groundwater models (comparison of the prediction made by a model to the actual outcome) show that many apparently well-calibrated models have not provided good predictions of future conditions (Konikow 1986; Anderson & Woessner 1992a), even in the absence of rapid climate change.

There are many reasons for these failures, but we will focus on two of the major causes: use of an inappropriate conceptual model and the lack of an appropriate calibration data set. Conceptual models that are inappropriate to the system being modeled may be chosen for two main reasons. First, even where a large observational data set is available for use in conceptual model development, historical data can often be interpreted to support more than one conceptual model, even though the different conceptual models will yield different predictions of future conditions (Bredehoeft 2003). Second, if existing data are insufficient, a seemingly valid conceptual model can be developed. Data collected after a conceptual model has been formulated often discredits the original conceptual model, a phenomenon referred to by Bredehoeft (2005) as ‘surprise’. Given that long-term observations of recharge are extremely rare, accurate framing of a conceptual model for a groundwater system and, more specifically, how recharge will respond to climatic change is difficult.

The shortness of most existing groundwater data sets also introduces uncertainty and errors into predictive models. In hydrologic modeling, a numerical model is considered to be ‘calibrated’ if its predictions match historical observations and, once calibrated, a model is typically assumed to be useful for predictions of future behavior, regardless of the time scale. In petroleum reservoir engineering, the term ‘history matching’ is used rather than calibration, and the ability of a model to predict future behavior without significant uncertainty is considered to be limited to the length of the history being matched (i.e. a 5-year history match allows good predictions no longer than 5 years into the future) (Bredehoeft 2003). Under this rule of thumb, given the typically short-term data sets used for groundwater-model calibrations, most models would not be considered adequate for predictions on the multi-decade and centennial time scales of climate change (Konikow & Person 1985).

Predictions

Nonetheless, modeling of future impacts, including groundwater impacts, is becoming more common as concerns increase regarding climate-change impacts on hydrologic systems. Predictions of climate-change impacts on groundwater systems differ from place to place, and model to model, depending on a number of factors. In some settings, increases in groundwater recharge are projected (e.g. van Roosmalen *et al.* 2007) while, in others, declines are projected (e.g. Younger *et al.* 2002; Brouyère *et al.* 2004). Recharge cannot be expected to change in the same way everywhere, but do these differing projections reflect only geographic differences? As discussed above, some of the differences may result from geographic differences or uncertainties regarding future climate conditions. As importantly, differences between predictions of future groundwater conditions may also reflect differences in the kinds of climatic variables and other processes and variables that the groundwater models incorporate or simulate. For instance, even under uniform changes in precipitation, areas with different soil characteristics can yield different groundwater responses (van Roosmalen *et al.* 2007).

Because of the importance of snowmelt to recharge in many parts of the world, a prediction of future recharge based solely on changes in precipitation amount without examining precipitation type could very poorly predict future recharge rates. Another potential source of projection error may be the highly nonlinear relations between precipitation and recharge, which ensure that changes in precipitation can cause disproportionate changes in recharge. Large geographic and scenario-to-scenario differences are to be expected. Two examples that allow such comparisons are a study by Sandström (1995) in which a model for a site in semi-arid Tanzania yielded a 50% decline in groundwater recharge in response to a 15% decline in precipitation, while a study by Green *et al.* (2007) for a range of climatic zones predicted increases in recharge ranging from 74 to 509% resulting from a 37% increase in precipitation. Thus it is vital that evaluations of climate-change vulnerabilities among groundwater systems be judged in the context of the particular processes and settings being modeled. Not all models, nor all scenario descriptions, will be equally valid or intercomparable for a given groundwater system.

MONITORING

Given these uncertainties and challenges concerning modeling approaches, monitoring of nearly all aspects of groundwater systems has become all the more necessary. Only by extending the lengths of records of groundwater levels, storage and quality can we begin to develop valid conceptual and numerical models, and to truly evaluate those models and concepts on time scales relevant to the climate-change problem. Only by availing ourselves of new monitoring methodologies that allow us to track variations in recharge and discharge on a full range of time scales can we improve and eventually validate the ways that we represent those variations in groundwater models and budgets. New hydraulic, geophysical, geochemical and even biological approaches have been developed in the past few decades that allow us to directly and indirectly measure time-varying recharge and discharge in ways that were not previously possible (Earman & Dettinger 2008). These methodologies should be considered for widespread and long-term deployment as monitoring networks that allow us to track changes that *will* impact groundwater storage and quality, whereas nearly all existing monitoring networks (based solely on observations of groundwater levels and chemical variations, e.g. Weider & Boutt (2010)) only measure changes in groundwater storage and quality that have already happened. Under a rapidly changing climate, the existing approach leaves our resources and management strategies vulnerable to being outstripped by changing times. In many developing nations with populations highly dependent on groundwater, there are even fewer data on water resources, making the need particularly dire (Taylor *et al.* 2009).

Historically most groundwater monitoring networks have focused on aquifers (and sections within aquifers) that have been most immediately impacted by pumpage. In order to prepare for potential climate-change influences on groundwater systems, a greater attention to conditions nearer recharge and natural discharge areas may be warranted (e.g. as in http://groundwaterwatch.usgs.gov/Net/OGWNetwork.asp?ncd=crn). Much of our lack of quantitative understanding of how climate influences recharge stems from our too-common lack of observational attention to recharge areas and to aquifers under natural conditions.

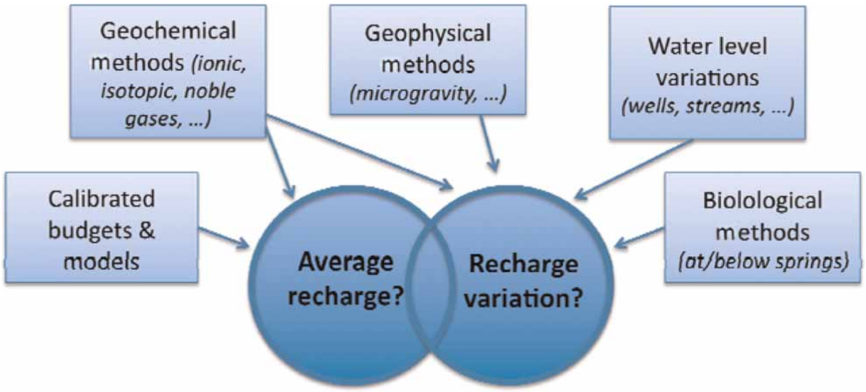

Figure 5 | Conceptual diagram illustrating various methods that can be used to estimate recharge *magnitude* (left circle) and recharge *change* (right circle).

Estimation of natural recharge rates has always been a difficult task because of its frequently dispersed and subterranean occurrence (Hogan *et al*. 2004). Most basin-scale recharge estimates have been derived by calibration of various local- to basin-scale water budgets or flow models, which is to say that recharge estimates are frequently derived as residuals obtained once other, more readily measured water budget elements have been determined. Uncertainties are thus typically large (de Vries & Simmers, 2002; Sophocleous 2004). However, in the context of potential climate-change impacts on recharge, the question may be different. In this context, the most pressing question is not necessarily 'how much overall recharge has occurred' but rather 'to what extent are recharge rates changing?'. Depending on the methods used, some estimates of recharge variability and trends can be obtained and couched as percentages of the long-term averages, even if those long-term averages are not known. The distinction between estimating absolute recharge volumes and relative recharge changes is important because, although options for measuring recharge in absolute terms are limited, a number of different strategies for measuring frequencies, magnitudes and percentage contributions of recharge events, mechanisms and changes have been developed in recent decades (Figure 5).

A recent review of options for detecting recharge change in California and Nevada (USA) discussed and compared widely differing hydraulic, geophysical, geochemical and biological methods for monitoring recharge variability and change (Earman & Dettinger 2008). Because accurate depictions of the influences of climate variability and change on recharge rates are absent or limited in many groundwater models, monitoring is the only immediate option for recognizing such changes if they occur. As we have more methods and options for monitoring recharge variability than directly measuring absolute recharge rates at basin or aquifer scales, the immediate focus may best be placed on monitoring recharge variation (Figure 5).

SUMMARY

Groundwater resources in different regions and aquifers will be affected by climate change in many different and differing ways. Even at the scale of a particular aquifer, major uncertainties exist regarding how climate may affect recharge, storage and discharge. These uncertainties result from uncertainties in projections of future climate, as well as from difficulties inherent in modeling the complex string of processes that can affect groundwater recharge, storage and discharge, and the fact that it is difficult to estimate groundwater recharge on a regional scale, even assuming unchanged climate conditions.

Although difficulties and uncertainties exist with regard to predictions, groundwater is a resource of vital importance, so a deeper understanding of how regional and local climate changes could affect groundwater systems is essential to proper water-resources management. This situation will require long-term observations of the interaction between climate and groundwater recharge, storage and discharge, as well as the development and testing of models that more completely represent both the long- and short-term connections between climate and groundwater, both in terms of water balances and water quality. Under changing climate conditions, sustained and regular monitoring targeted at the responses of groundwater systems to climate is becoming all the more crucial. The resulting improvements in understanding the potential impacts of climate change on groundwater should help groundwater managers to identify and design adaptation options, including managed aquifer recharge and conjunctive use programs, appropriate for their particular systems. Beyond this factor, groundwater and groundwater vulnerabilities need to be included in water-resources management and in climate-change assessments more generally.

ACKNOWLEDGEMENTS

We appreciate comments from Jim Thomas of the Desert Research Institute, Reno, NV, Sushel Unninayar of NASA Gil Zemansky of GNS, and two anonymous reviewers that led to significant improvements in the manuscript. Funding from the United States Geological Survey (USGS) Office of Groundwater and the California Energy Commission played an important role in initiating many of the considerations presented here.

REFERENCES

Akuoko-Asibey, A., Nkemdirim, L. C. & Draper, D. L. 1993 The impact of climatic variables on seasonal water consumption in Calgary, Alberta. *Can. Water Res. J.* **18**, 107–116.

Alley, W. M. 2007 Another water budget myth: the significance of recoverable ground water in storage. *Ground Water* **45**, 251.

Anderson, M. P. & Woessner, W. W. 1992a The role of postaudit in model validation. *Adv. Water Res.* **15**, 167–173.

Anderson, M. P. & Woessner, W. W. 1992b *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*. Academic, San Diego, CA.

Bales, R., Molotch, N., Painter, T., Dettinger, M., Rice, R. & Dozier, J. 2006 Mountain hydrology of the western US. *Water Res. Res.* **42**, W08432.

Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. 2005 Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**, 303–309.

Bazzaz, F. & Sombroek, W. 1996 *Global Climate Change and Agricultural Production: Direct and Indirect Effects of Changing Hydrological Soil and Plant Physiological Processes*. Food and Agriculture Organization of the United Nations/John Wiley & Sons, Chichester.

Betts, R. A., Boucher, O., Collins, M., Cox, P. M., Falloon, P. D., Gedney, N., Hemming, D. L., Huntingford, C., Jones, C. D., Sexton, D. M. H. & Webb, M. J. 2007 Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature* **448**, 1037–1041.

Bredehoeft, J. D. 2003 From models to performance assessment: the conceptualization problem. *Ground Water* **41**, 571–577.

Bredehoeft, J. 2005 The conceptualization model problem – surprise. *Hydrogeol. J.* **13**, 37–46.

Brouyère, S., Carabin, G. & Dassargues, A. 2004 Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium. *Hydrogeol. J.* **12**, 123–134.

Chen, C.-C., Gillig, D. & McCarl, B. A. 2001 Effects of climatic change on a water dependent regional economy: a study of the Texas Edwards Aquifer. *Climate Change* **49**, 397–409.

Chen, Z., Grasby, S. E. & Osadetz, K. G. 2004 Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. *J. Hydrol.* **290**, 43–62.

Chiew, F. H. S., Teng, J., Vaze, J., Post, D. A., Perraud, J. M., Kironon, D. G. C. & Viney, N. R. 2009 Estimating climate change impact on runoff across southeast Australia: method, results, and implications of the modeling method. *Water Res. Res.* **45**, W10414.

Committee on Hydrologic Science 2004 Interactions of groundwater with climate. In: *Groundwater Fluxes Across Interfaces*. National Academies Press, Washington, DC, pp. 32–41.

Coutant, C. C. 1999 *Perspectives on Temperature in the Pacific Northwest's Fresh Waters*. Oak Ridge National Laboratory Environmental Sciences Division Publication 4849 (ORNL/TM-1999/44), Oak Ridge, Tennessee.

Croley, T. E. & Luukkonen, C. L. 2003 Potential effects of climate change on ground water in Lansing, Michigan. *J. AWRA* **39**, 149–163.

Cruz, F. T., Pitman, A. J. & McGregor, J. L. 2010 Probabilistic simulations of the impact of increasing leaf-level atmospheric carbon dioxide on the global land surface. *Climate Dyn.* **34**, 361–379.

Daly, C., Neilson, R. P. & Phillips, D. L. 1994 A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteorol.* **33**, 140–158.

de Vries, J. J. & Simmers, I. 2002 Groundwater recharge: an overview of processes and challenges. *Hydrogeol. J.* **10**, 5–17.

Dettinger, M. D. & Culberson, S. 2008 Internalizing climate change – scientific resource management and the climate change challenges. *San Francisco Estuary Watershed Sci.* **6**, article 5.

Dettinger, M. & Earman, S. 2007 Western ground water and climate change –pivotal to supply sustainability or vulnerable in its own right? *Ground Water News Views* **4**, 4–5.

Döll, P. 2009 Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environ. Res. Lett.* **4**, 035006.

Dow, C. L. & DeWalle, D. R. 2000 Trends in evaporation and Bowen ratio on urbanizing watersheds in eastern United States. *Water Res. Res*. **36**, 1835–1843.

Earman, S. & Dettinger, M. 2008 *Monitoring networks for long-term recharge change in the mountains of California and Nevada. In California Energy Commission PIER Workshop Paper CEC-500-2008-006*. Available from: http://www.energy.ca.gov/2008publications/CEC-500-2008-006/CEC-500-2008-006.PDF.

Earman, S., Campbell, A. R., Newman, B. D. & Phillips, F. M. 2006 Isotopic exchange between snow and atmospheric water vapor: estimation of the snowmelt component of groundwater recharge in the southwestern United States. *J. Geophys. Res*. **111**, D09302.

Eckhardt, K. & Ulbrich, U. 2003 Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. *J. Hydrol*. **284**, 244–252.

Eckstein, G. & Eckstein, Y. 2003 A hydrogeological approach to transboundary ground water resources and international law. *Am. Univ. Int. Law Rev*. **19**, 201–258.

Ferguson, G. & St. George, S. 2003 Historical and estimated ground water levels near Winnipeg, Canada, and their sensitivity to climatic variability. *J. AWRA* **39**, 1249–1259.

Fetter, C. W. 2001 *Applied Hydrogeology*, 4th edition. Prentice-Hall, Englewood Cliffs, NJ.

Fleming, S. W. & Quilty, E. J. 2006 Aquifer responses to El Niño-Southern Oscillation, southwest British Columbia. *Ground Water* **44**, 595–599.

Flint, A. L., Flint, L. E., Hevesi, J. A. & Blainey, J. B. 2004 Fundamental concepts of recharge in the desert Southwest: a regional modeling perspective. In: *Groundwater Recharge in a Desert Environment: The Southwestern United States* (J. F. Hogan & F. M. Phillips & B. R. Scanlon, eds.). American Geophysical Union, Washington, DC, pp. 159–184.

Freeze, R. A. & Cherry, J. A. 1979 *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ.

Genereux, D. P. & Hooper, R. P. 1998 Oxygen and hydrogen isotopes in rainfall-runoff studies. In: *Isotope Tracers in Catchment Hydrology* (C. Kendall & J. J. McDonnell, eds.). Elsevier, Amsterdam, pp. 319–346.

Graham, R. C., Hirmas, D. R., Wood, Y. A. & Amrhein, C. 2008 Large near-surface nitrate pools in soils capped by desert pavement in the Mojave Desert, California. *Geology* **36**, 259–262.

Green, T. R., Bates, B. C., Charles, S. P. & Fleming, P. M. 2007 Physically based simulation of potential effects of carbon dioxide–altered climates on groundwater recharge. *Vadose Zone J*. **6**, 597–609.

Gurdak, J. J., Hanson, R. T., McMahon, P. B., Bruce, B. W., McCray, J. E., Thyne, G. D. & Reedy, R. C. 2007 Climate variability controls on unsaturated water and chemical movement, High Plains Aquifer, USA. *Vadose Zone J*. **6**, 533–547.

Hanson, R. T. & Dettinger, M. D. 2005 Ground water/surface water responses to global climate simulations, Santa Clara-Calleguas Basin, Ventura, California. *J. AWRA* **41**, 517–536.

Hem, J. D. 1992 *Study and Interpretation of the Chemical Characteristics of Natural Water*, 3rd edition. US Geological Survey Water-Supply Paper 2254, Washington, DC.

Heppner, C. S., Nimmo, J. R., Folmar, G. J., Gburek, W. J. & Risser, D. W. 2007 Multiple-methods investigation of recharge at a humid-region fractured rock site, Pennsylvania, USA. *Hydrogeol. J*. **15**, 915–927.

Herrera-Pantoja, M. & Hiscock, K. M. 2008 The effects of climate change on potential groundwater recharge in Great Britain. *Hydrol. Process*. **22**, 73–86.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G. & Jarvis, A. 2005 Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol*. **25**, 1965–1978.

Hogan, J. F., Phillips, F. M. & Scanlon, B. R. 2004 Preface. In: *Groundwater Recharge in a Desert Environment: The Southwestern United States* (J. F. Hogan, F. M. Phillips & B. R. Scanlon, eds.). American Geophysical Union, Washington, DC, pp. vii.

Howard, K. & Griffith, A. 2009 Can the impacts of climate change on groundwater resources be studied without the use of transient models? *Hydrol. Sci. J*. **54**, 754–764.

Hutson, S. S., Barber, N. L., Kenny, J. F., Linsey, K. S., Lumia, D. S. & Maupin, M. A. 2004 *Estimated Use of Water in the United States in 2000*. US Geological Survey Circular 1268, Washington, DC.

Intergovernmental Panel on Climate Change 2007 Summary for policymakers. In: *Climate Change 2007 The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Available from: http://water.state.co.us/DWRIpub/DWR%20Presentations/kknox_090606.pdf.

Jones, I. C. & Banner, J. L. 2003 Hydrogeologic and climatic influences on spatial and interannual variation of recharge to a tropical karst island aquifer. *Water. Res. Res*. **39**, 1253.

Kayane, I. 1997 Global warming and groundwater resources in arid lands. In: *Freshwater Resources in Arid Lands: UNU Global Environmental Forum V* (J. I. Uitto & J. Schneider, eds.). United Nations University Press, Tokyo, pp. 70–80.

Kimmerer, W. J. 2002 Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? *Mar. Ecol. Prog. Ser*. **243**, 39–55.

Knowles, N., Dettinger, M. D. & Cayan, D. R. 2006 Trends in snowfall versus rainfall in the western United States. *J. Climate* **19**, 4545–4559.

Knox, K. 2006 *The Republican River, Colorado State Engineer's Office Conference*. Available from: http://water.state.co.us/DWRIpub/DWR%20Presentations/kknox_090606.pdf.

Konikow, L. F. 1986 Predictive accuracy of a ground–water model – lessons from a postaudit. *Ground Water* **24**, 173–184.

Konikow, L. F. & Person, M. 1985 Assessment of long-term salinity changes in an irrigated stream-aquifer system. *Water Res. Res*. **21**, 1611–1624.

Loaiciga, H. A. 1999 Direct groundwater fluxes under 2xCO_2 global warming scenario. *Water Res*. **26**, 126–131.

Loáiciga, H. A. 2003 Climate change and ground water. *Annals. Assoc. Am. Geographers* **93**, 30–41.

Malcom, R. & Soulsby, C. 2000 Modelling the potential impact of climate change on a shallow coastal aquifer in northern Scotland. In: *Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology* (N. S. Robbins & B. D. R. Misstear, eds.). Special Publication 182. Geological Society Special Publication 182, London, pp. 191–204.

Markstrom, S. L., Niswonger, R. G., Regan, R. S., Prudic, D. E. & Barlow, P. M. 2008 GSFLOW – coupled ground-water and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). In: *Chapter 1 of Section D, Ground-Water/Surface-Water Book 6, Modeling Techniques*. US Geological Survey, Washington, DC.

Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P. & Nijssen, B. 2002 A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. *J. Climate* **15**, 3237–3251.

McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. & White, K. S. 2001 Climate change 2001: impacts, adaption and vulnerability. In: *Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Available from: http://www.grida.no/climate/ipcc_tar/wg2/index.html.

Mote, P. W. 2003 Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophys. Res. Lett.* **30**, 1601.

Mote, P. W., Hamlet, A. F., Clark, M. P. & Lettenmaier, D. P. 2005 Declining mountain snowpack in western North America. *Bull. Am. Meteorol. Soc.* **86**, 39–49.

Person, M., Roy, P., Wright, H., Gutowski, W., Ito, E., Winter, T., Rosenberry, D. & Cohen, D. 2007 Hydrologic response of the Crow Wing Watershed, Minnesota, to mid-Holocene climate change. *Geol. Soc. Am. Bull.* **119**, 363–376.

Piggott, A., Brown, D., Moin, S. & Mills, B. 2001 *Exploring the dynamics of groundwater and climate interaction*. In *Proceedings of the 54th Canadian Geotechnical and 2nd Joint IAH-CNC and CGS Groundwater Specialty Conference, Canadian Geotechnical Society and the Canadian National Chapter of the International Association of Hydrogeologists, Canadian Geotechnical Society*, *Richmond, BC*, pp. 401–408.

Rahmstorf, S. 2007 A semi-empirical approach to projecting future sea-level rise. *Science* **315**, 368–370.

Ranjan, P., Kazama, S. & Sawamoto, M. 2006 Effects of climate change on coastal fresh groundwater resources. *Global Environ. Change* **16**, 388–399.

Rosenberg, N. J., Epstein, D. J., Wang, D., Vail, L., Srinivasan, R. & Arnold, J. G. 1999 Possible impacts of global warming on the hydrology of the Ogallala Aquifer region. *Clim. Change* **42**, 677–692.

Sada, D. W., Williams, J. E., Silvey, J. C., Halford, A., Ramakka, J., Summers, P. & Lewis, L. 2001 *A Guide to Managing, Restoring, and Conserving Springs in the Western United States*. US Bureau of Land Management Technical Reference 1737-17, BLM/ST/ST-01/001+1737, Denver, CO.

Sandström, K. 1995 Modeling the effects of rainfall variability on groundwater recharge in semi-arid Tanzania. *Nord. Hydrol.* **26** (4–5), 313–330.

Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E. & Dennehy, K. F. 2005 Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biol.* **11**, 1577–1593.

Scanlon, B. R., Reedy, R. C. & Tachovsky, J. A. 2007 Semiarid unsaturated zone chloride profiles: archives of past land use change impacts on water resources in the southern High Plains, United States. *Water Res. Res.* **43**, W06423.

Scibek, J. & Allen, D. M. 2006 Modeled impacts of predicted climate change on recharge and groundwater levels. *Water Res. Res.* **42**, 165–181.

Scibek, J., Allen, D. M., Cannon, A. J. & Whitfield, P. H. 2007 Groundwater–surface water interaction under scenarios of climate change using a high-resolution transient groundwater model. *J. Hydrol.* **333**, 165–181.

Sherif, M. M. & Singh, V. P. 1999 Effect of climate change on sea water intrusion in coastal aquifers. *Hydrol. Process* **13**, 1277–1287.

Simpson, E. S., Thorud, D. B. & Friedman, I. 1972 *Distinguishing seasonal recharge to groundwater by deuterium analysis in southern Arizona, world water Balance*. In *World Water Balance: Proceedings of the Reading Symposium, July 1970*, Vol. 3, International Association of Scientific Hydrology-UNESCO-WMO Studies and Reports in Hydrology, vol.11; Publication No 94 of the International Association of Scientific Hydrology, *Gentbrugge, Belgium*, pp. 623–633.

Sophocleous, M. 2004 Groundwater recharge. In: *Encyclopedia of Life Support Systems (EOLSS)*. Eolss Publishers, Oxford.

Soulsby, C., Tetzlaff, D., Bedem, N. V. D., Malcolm, I. A., Bacon, P. J. & Youngson, A. F. 2007 Inferring groundwater influences on surface water in montane catchments from hydrochemical surveys of springs and streamwaters. *J. Hydrol.* **333**, 199–213.

Sternberg, L. & Deniro, M. J. 1983 Isotopic composition of cellulose from C_3, C_4, and CAM plants growing near one another. *Science* **220**, 947–949.

Sugita, F. & Nakane, K. 2007 Combined effects of rainfall patterns and porous media properties on nitrate leaching. *Vadose Zone J.* **6**, 548–553.

Tanco, R. & Kruse, E. 2001 Prediction of seasonal water-table fluctuations in La Pampa and Buenos Aires, Argentina. *Hydrogeol. J.* **9**, 339–347.

Taylor, R. G., Koussis, A. D. & Tindimugaya, C. 2009 Groundwater and climate in Africa – a review. *Hydrol. Sci. J.* **54**, 655–664.

Thomson, A. M., Brown, R. A., Rosenberg, N. J., Srinivasan, R. & Izaurralde, R. C. 2005 Climate change impacts for the conterminus USA: an integrated assessment. *Climate Change* **69**, 67–88.

van Roosmalen, L., Christensen, B. S. B. & Sonnenborg, T. O. 2007 Regional differences in climate change impacts on groundwater and stream discharge in Denmark. *Vadose Zone J.* **6**, 554–571.

Viessman, W. Jr., Lewis, G. L. & Knapp, J. W. 1989 *Introduction to Hydrology*, 3rd edition. HarperCollins, New York.

Walvoord, M. A., Phillips, F. M., Stonestrom, D. A., Evans, R. D., Hartsough, P. C., Newman, B. D. & Striegl, R. G. 2003 A reservoir of nitrate beneath desert soils. *Science* **302**, 1021–1024.

Ward, J. K., Tissue, D. T., Thomas, R. B. & Strain, B. R. 1999 Comparative responses of model C3 and C4 plants to drought in low and elevated CO_2. *Global Change Biol.* **5**, 857–867.

Weider, K. & Boutt, D. F. 2010 Heterogeneous water table response to climate revealed by 60 years of ground water data. *Geophys. Res. Lett.* **37**, L24405.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R. & Swetnam, T. W. 2006 Warming and earlier spring increase western U.S. wildfire activity. *Science* **313**, 940–943.

Winograd, I. J., Riggs, A. C. & Coplen, T. B. 1998 The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada, USA. *Hydrogeol. J.* **6**, 77–93.

Wissmar, R. C., Smith, J. E., Li, H. W., Reeves, G. H. & Sedel, J. R. 1994 *Ecological Health of River Basins in Forested Regions of Eastern Washington and Oregon*. USDA Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR-326, Portland, OR.

Younger, P. L., Teutsch, G., Custudio, E., Elliot, T., Manzano, M. & Sauter, M. 2002 Assessments of the sensitivity to climate change of flow and natural water quality in four major carbonate aquifers of Europe. In: *Sustainable Groundwater Development* (K. M. Hiscock, M. O. Rivett & R. M. Davison, eds.). Geological Society Special Publication No. 193, London, pp. 303–323.

Zektser, I. S. & Everett, L. G. 2004 *Groundwater Resources of the World and Their Use, IHP-VI*. Series on Groundwater No. 6. United Nations Educational, Scientific and Cultural Organization, Paris.

First received 27 May 2010; accepted in revised form 13 January 2011