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Introduction

In a recent issue of this journal, Alcamo *et al* (2008) put forward a 'grand challenge for freshwater research' calling for new thinking on the global water system defined by the interactions of the physical water cycle from local to global scales, biogeochemical processes, and anthropogenic factors. Alcamo *et al* also highlighted long-distance cause-and-effect connectivities and regional vulnerabilities in response to changes to the global water system. Groundwater is an important component of the freshwater system and its role is becoming even more prominent as the more accessible surface water resources become increasingly exploited to support increasing populations and development. Yet despite its significance, there has been comparatively little research conducted on groundwater relative to surface water resources, particularly in the context of climate change impact assessment (Bates *et al* 2008). This focus issue has therefore been assembled to expand upon the currently limited knowledge of groundwater systems and their links with climate. Many of the papers included here explore the interrelated issues of groundwater resources, climate-related changes and vulnerabilities at a regional scale in different continents and globally.

The role of groundwater

Other than water stored as ice, groundwater is by far the largest freshwater resource on Earth. It is a relatively clean, reliable and cost-effective resource, especially in areas with limited surface water supply such as parts of Africa which are almost wholly dependent on groundwater. It is therefore no surprise that groundwater plays an important role as drinking water and for irrigation in agriculture, with an estimated 40% of the world's food produced by irrigated farming (Shiklomanov 1997). Groundwater also plays a significant role in maintaining surface water systems through flows into lakes and baseflow to rivers. These 'environmental flows' are often crucial for maintaining the biodiversity and habitats of sensitive ecosystems (Tharme 2002). However, all of these functions become increasingly vulnerable as changes in climate occur.

Climate change

As reported by the IPCC, during the 20th century, precipitation totals have mainly increased over land in high northern latitudes and decreased in some sub-tropical and lower mid-latitude regions. Global average air and ocean temperatures have also increased and over the past 50 years hot days, hot nights and heatwaves have become more frequent. Climate model simulations suggest that these trends will continue into the 21st century (Bates *et al* 2008). It is not only precipitation totals which are likely to change but also precipitation intensities and variability. Since the 1970s the frequency of heavy precipitation events has increased whilst the area of land classified as very dry has more than doubled (Bates *et al* 2008). These climatic extremes are likely to cause increased frequencies of severe droughts and floods.

Climate-related impacts on groundwater

Changing precipitation patterns together with increased evapotranspiration linked to increased temperatures will affect groundwater recharge rates and the depths of groundwater tables. As Shah (2009, this issue) points out, in humid areas, higher precipitation variability may negatively impact natural recharge as there is evidence to suggest that the ratio of runoff to precipitation increases with rainfall intensity. In arid and semi-arid regions however, increased precipitation variability may increase recharge because only high-intensity rainfall is able to infiltrate fast enough before evaporating (Bates *et al* 2008). Thus, the net impact on a given location will depend upon the change in both the total precipitation and the variability of that precipitation.

Aquifers respond to droughts and climate fluctuations much more slowly than surface storages; as a result, compared to surface storages, aquifers act as a more resilient buffer during dry spells especially when they have a large storage capacity (Shah 2009, this issue). Climate-related impacts on the depths of groundwater tables are therefore difficult to establish over short-timescales and long-term data are usually lacking. Some evidence exists that groundwater levels in aquifers located near Winnipeg, Canada, are correlated with 3–4 year annual temperature and precipitation changes with lags up to 24 months although so far long-term climate-related trends have not been observed (Ferguson and George 2003). Loáiciga (2009, this issue) finds that long-term climate-related trends are also absent in observations of groundwater levels in the Edwards aquifer in Texas but that groundwater levels have nevertheless been declining due to groundwater pumping surpassing groundwater recharge rates; a situation currently found in several other aquifers worldwide (Ferguson and George 2003, Bates *et al* 2008). On the other hand, Toews and Allen (2009, this issue) find that the most noticeable change in the water budget in the Oliver region of British Columbia, Canada, for future time periods (2050s and 2080s) under a simulated future climate change scenario, is the increased contribution of recharge to the annual water budget, related primarily to increases in irrigation return flow resulting from higher irrigation needs under warmer temperatures and a longer growing season, and culminating in elevated water tables. Both the studies by Loáiciga and Toews and Allen emphasize respectively that irrigation and irrigation return flows cannot be disregarded in groundwater-related climate change impact studies.

Shah (2009, this issue) raises another important, yet not obvious, issue relating to India's booming 'water-scavenging' irrigation economy whereby groundwater-sourced irrigation has direct feedbacks to climate through the use of energy-inefficient technologies for groundwater pumping. Groundwater irrigation is energy-intensive and the bulk of energy used in pumping groundwater uses diesel or electricity generated with coal which currently produces an estimated 4–6% of India's total carbon emissions. The explosive growth in groundwater demand during recent decades is likely to continue in the wake of climate change as countries such as India strive for improved food security. Shah therefore postulates that India needs to maximize both water productivity and energy efficiency and make a transition from surface storages to 'managed aquifer storages'. This energy–irrigation nexus holds the key to minimizing the carbon footprint of Indian irrigation.

Excessive groundwater extraction can also cause problems relating to subsidence and saltwater intrusion (see Narasimhan 2009, this issue) for example in coastal cities in Asia, where serious structural and flooding problems have occurred (Taniguchi *et al* 2008). Asian cities are not only subject to subsidence and saltwater intrusion however, but as Taniguchi *et al* (2003) and Taniguchi (2009, submitted) point out, groundwater temperatures can be affected by surface warming due to both climate change and urban 'heat island' effects leading to thermal signals of up to 100 m depth into the subsurface environment.

Resident times for storage and transfer of solutes in groundwater are much greater than for surface water systems, which can be problematic if groundwater resources are not properly protected as changes in the balance between surface and subsurface runoff pathways will affect nutrient leaching from soils into groundwater and may cause problems with pollution (e.g. Olli *et al* 2009). Irrespective of future climate scenarios however, groundwater nutrient loads appear likely to increase as they are controlled primarily by the delayed load from historical agricultural land management practices (Destouni and Darracq 2009, submitted), (the so-called 'nutrient time-bomb').

Vulnerability and future management

In many cases, the people most vulnerable to these changes are those in less economically developed countries who do not have the adaptive capacity for change so there may be a significant impact on international efforts towards poverty alleviation and the achievement of the Millennium Development Goals. Döll (2009, this issue) finds that countries such as India, Pakistan, Iran, Saudi Arabia, Morocco and eastern China have particularly high sensitivity indices as they suffer from strong water scarcity, take more than 30% of their water supply from groundwater and have a low to medium human development indicator. Many African countries and semi-arid regions of Mexico, southwest USA and Australia also have high sensitivity indices. Over 15% of the global population could be affected by a decrease in renewable groundwater resources of at least 10% in the future (Döll 2009, this issue).

Adaptive management is seen as a key component which is particularly relevant to groundwater; it is also a central concept in Earth systems engineering, which views sustainable solutions as requiring a whole systems approach which integrates coupled human and natural systems, echoing the messages of Alcamo *et al* (2008). The adaptation measures needed to respond to changes in groundwater systems through climate change impacts can only be formulated based on a solid foundation of observations over long time scales. There is therefore a substantial need to continuously monitor groundwater systems and recharge (Narasimhan 2009, this issue). There is also a need to improve on computational models related to the hydrological cycle at scales relevant to decision making (Bates *et al* 2008).

The studies presented in this focus issue clearly show that groundwater is an important resource that is particularly vulnerable to the direct or indirect effects of climate change and so needs careful management. As Narasimhan (2009, this issue) points out, we have reached the current point through a historical trajectory that has already left a legacy that will need to be managed in the future. The technological advances achieved in the 19th and 20th centuries are not sufficient alone to manage the 'common good' that is groundwater; institutional and political governance structures are also important.

Developing methods and policies for sustainable use of global resources such as groundwater in response to climate-driven hydrologic changes in combination with additional stresses from population growth and consumption and associated land-use/land-cover changes will be the major water management challenge in the 21st century.

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