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Special Section: Groundwater Resources Assessment under the Pressures of Humanity and Climate Change

Potential Impacts of Climate Change and Human Activity on Subsurface Water Resources

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In recent decades, atmospheric concentrations of carbon dioxide and other greenhouse gases have risen dramatically (Keeling and Whorf, 2005). The consequent effects on global and regional climates are uncertain (Barnett et al., 2006; Hennessy et al., 2006; Karl and Trenberth, 2003; Wentz et al., 2007) and remain controversial (Hegerl et al., 2007; Lovell, 2006; Schneider, 2001; Schneider, 2007), but the potential impacts of changes in the mean and variance of climate variables on hydrology must be anticipated with careful investigations. Although significant progress has been made toward assessments of surface hydrology and associated ecosystems (McCarthy et al., 2001; Adger et al., 2007), little is known about how subsurface waters in the vadose zone and groundwater might respond to climate change and variability (Sophocleous, 2004). Furthermore, most groundwater systems have already been altered by human activities that are not necessarily related to climate change. Thus, there are urgent and ongoing needs to address the expected coupled effects of human activities and climate change.

The vadose zone acts as an important component of the global water cycle; it is commonly the major interface between the atmosphere and the saturated zone. Important controls on groundwater quantity and quality, including plant water uptake, water redistribution and storage, and biochemical transformations, exist in the vadose zone. Most of the processes involved can have nonlinear responses to atmospheric conditions associated with climate change and/or terrestrial surface conditions associated with human activities. Thus, groundwater assessments under the coupled pressures of human activities and climate change and variability involve exploration of complex system interactions. Multidisciplinary scientific approaches offer the most rigorous platforms to address such complexity. Furthermore, assessments go beyond physical, chemical, and biological interactions, such that human systems of resource management and governmental policies must be considered.

This special section of *Vadose Zone Journal* is an outcome of the international conference on Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) that was held in Kyoto, Japan on 4–6 April 2006. Sponsored by UNESCO's International Hydrological Program, GRAPHIC is a collaborative effort and umbrella for international research and education, and the conference was hosted by the Research Institute for Humanity and Nature, Japan. The GRAPHIC project has outlined areas of desired international investigations covering major geographical regions, groundwater resource topics, and methods to help advance the combined knowledge needed to address the science and social aspects. This special section includes studies of several locations around the world, including regions of Africa, Asia, Australia, Micronesia, North America, and Europe. These case studies, which are summarized below, are merely a sample of the global work and interest, reflecting some of the recent activities in this fledgling area of international research.

Gurdak et al. (2007) monitored water and chemical movement in the vadose zone at multiple sites across the High Plains aquifer, USA, showing that the spectra of subsurface responses were related to climate variability ranging from El Niño Southern Oscillation (ENSO periods of 2–6 yr) to multidecadal timescales. Most of the variance in groundwater levels was correlated with Pacific Decadal Oscillations in climate, particularly in the Southern High Plains aquifer. Spatial variability in recharge and other factors are cited in this study, and Gurdak et al. (2007) note the relevance of system response times to human life cycles.

Water and chemical fluxes in the shallow subsurface were also investigated through laboratory experiments using different soil/porous media layering (Sugita et al., 2007). Effects of rainfall intensity and timing on nitrate leaching in sand and macroporous, layered media were measured, and expected changes in rainfall patterns under climate changes were estimated to increase the probability of leaching by at least 25% in parts of Japan. Sugita et al. (2007) also found that soil heterogeneity was an important factor affecting flow paths and available "hot spots" for denitrification at lower leaching rates. Such careful measurements provide process information that may be scaled up in future work to provide regional assessments of potential climate change and variability impacts.

A study of projected regional climate change effects on groundwater recharge, storage, and discharge to streams in Denmark was conducted by van Roosmalen et al. (2007) using a distributed hydrological simulation

Abbreviations: ENSO, El Niño Southern Oscillation; GRAPHIC, Groundwater Resources Assessment under the Pressures of Humanity and Climate Change.

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model. Precipitation, temperature, and potential evapotranspiration were predicted to increase in each of two 30-yr climate scenarios. Groundwater recharge and resulting subsurface storage and discharge were predicted to increase in sandy soils, while only small changes were predicted in clayey sediment and soils. Climate change effects on groundwater recharge and discharge to streams were found to vary seasonally.

Potential effects of climate change on water availability were also predicted to vary seasonally in Kenya, where water shortages were projected to increase by the year 2100 if there are no infrastructure changes (Aerts et al., 2007). The authors explored the function and robustness of "sand dams" built to make artificial shallow aquifers in stream beds to reduce the evaporation of stored waters. If the number of sand dams will be tripled in the future from about 500 to 1500, subsurface water availability could increase under climate change, again with a strong seasonal effect. Aerts et al. (2007) highlight the importance of climate change effects on the temporal variability of water resources in this region of Africa.

White et al. (2007) relate the groundwater hydrology of an atoll in the Republic of Kiribati (formerly the Gilbert Islands) to droughts associated with ENSO climate variability. Shallow groundwater responds rapidly to rainfall events, pumping, and ocean tides due to high hydraulic conductivities of the coral sands, such that water quality is vulnerable to climatic events and human activities. Social aspects of adaptation to climate change include appropriate communication with the island community to improve knowledge and long-term planning.

Groundwater quality may also be related to long-term changes in atmospheric temperatures that propagate into the subsurface. A regional study in Asia by Taniguchi et al. (2007) demonstrates the concepts and use of borehole temperature logs to assess combined changes in regional temperatures and "heat islands" caused by urbanization. The study region included urban areas of Tokyo, Osaka, Seoul, and Bangkok, each with different histories of urbanization and associated surface warming. Temperature deviations from estimates of the local mean geothermal gradients were used to infer the timings of surface warming, and such temperature perturbations were found to propagate from 50 to 140 m deep.

Finally, Green et al. (2007) developed and demonstrate a method for simulating climate change effects on vegetation and soil-water regimes affecting groundwater recharge at two sites in Australia with Mediterranean and subtropical climates. Historical climates at each site and dynamic equilibrium climates simulated with a general circulation model assuming a doubling of atmospheric CO_2 concentration were used to generate sequences of cross-correlated daily weather variables for each climate scenario. The authors found that vegetation and soil characteristics jointly controlled the nonlinear changes in recharge at each location. This study and the other studies in this special section indicate the ongoing need to improve our understanding and ability to predict terrestrial and subsurface responses to climate change and variability affecting groundwater systems.

The range of geographic locations, topics, and methods explored across the seven studies reported in this section is quite broad. Yet, it is not difficult to identify gaps in the present coverage of problem areas, scientific methods, and generalization of results from both empirical and theoretical investigations. The scientific community has yet to focus its combined expertise and effort on integrative and complementary research needed to provide the basis for confident assessments of the coupled effects of human activities and global climate change on subsurface water fluxes, storage, and biochemical quality issues. Organizations and collaborative efforts such as GRAPHIC can help move scientists toward proactive investigations of likely responses of groundwater systems to the impending pressures of humanity and climate change.

References

Adger, N., et al. 2007. Climate change 2007. Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Summary for Policymakers. Available at http://static.scribd.com/docs/kcpgxma2ohgse.pdf (verified 21 May 2007). Intergovernmental Panel on Climate Change.

Aerts, J., R. Lasage, W. Beets, H. de Moel, and A. de Vries. 2007. Robustness of sand storage dams under climate change. Vadose Zone J. 6:572–580 (this issue).

Barnett, D.N., S.J. Brown, J.M. Murphy, D.M.H. Sexton, and M.J. Webb. 2006. Quantifying uncertainty in changes in extreme event frequency in response to doubled CO_2 using a large ensemble of GCM simulations. Clim. Dyn. 26:489–511.

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

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

Hegerl, G.C., T.J. Crowley, W.T. Hyde, and D.J. Frame. 2007. Climate modelling: Uncertainty in climate-sensitivity estimates (reply). Nature 446:E2.

Hennessy, K.J., I. Macadam, and P.H. Whetton. 2006. Climate change scenarios for initial assessment of risk in accordance with risk management guidance. Available at http://www.greenhouse.gov.au/impacts/publications/pubs/risk-scenarios.pdf (verified 23 July 2007). CSIRO Marine and Atmospheric Reserach, Aspendale, VIC, Australia.

Karl, T.R., and K.E. Trenberth. 2003. Modern global climate change. Science 302:1719–1723.

Keeling, C.D., and T.P. Whorf. 2005. Atmospheric CO_2 records from sites in the SIO air sampling network. *In* Trends: A compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, USDOE, Oak Ridge, TN.

Lovell, B. 2006. Climate change: Conflict of observational science, theory, and politics, discussion. AAPG Bull. 90:405–407.

McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White. 2001. Climate change 2001: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Third Assessment Report of the IPCC. Available at http://www.grida.no/climate/ipcc_tar/wg2/index.htm (verified 1 May 2007). Intergovernmental Panel on Climate Change.

Schneider, S.H. 2001. What is "dangerous" climate change? Nature 411:17–19.

Schneider, T. 2007. Climate modelling: Uncertainty in climate-sensitivity estimates. Nature 446:E1.

Sophocleous, M. 2004. Climate change: Why should water professionals care? Ground Water 42:637.

Sugita, F., and K. Nakane. 2007. Combined effects of rainfall patterns and porous media properties on nitrate leaching. Vadose Zone J. 6:548–553 (this issue).

Taniguchi, M., T. Uemura, and K. Jago-on. 2007. Combined effects of urbanization and global warming on subsurface temperature in four Asian cities. Vadose Zone J. 6:591–596 (this issue).

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

Wentz, F.J., L. Ricciardulli, K. Hilburn, and C. Mears. 2007. How much more rain will global warming bring? Science doi:10.1126/science.1140746.

White, I., A.C. Falkland, T. Metutera, E. Metai, M. Overmars, P. Perez, and A. Dray. 2007. Climatic and human influences on groundwater in low atolls. Vadose Zone J. 6:581–590 (this issue).