The return of groundwater quantity: a mega-scale and interdisciplinary "future of hydrogeology"?

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Keywords Water supply · Hydraulic properties · Groundwater recharge/water budget · Groundwater management

A series of recent papers suggest groundwater quantity may be returning to prominence in hydrogeology research. The unsustainable depletion of groundwater has been documented on both regional (Rodell et al. 2009; Tiwari et al. 2009; Famiglietti et al. 2011) and global scales (Wada et al. 2010; Konikow 2011; Wada et al. 2012) using data synthesis and the GRACE satellite data. Additionally, how groundwater resources will be impacted by global change remains important but uncertain and difficult to predict (Green et al. 2011; Taylor et al. 2013). Recent discussions on groundwater sustainability have suggested applying cutting-edge sustainability concepts such as multi-generational goal setting and adaptive management to groundwater quantity problems (Gleeson et al. 2010, 2012).

At its core, groundwater quantity is a water budget question of fluxes and stores. The critical applied questions of groundwater quantity are "how much groundwater is available for sustainable use, and what is the impact of the various uses on interconnected social, economic and environmental systems" From the perspective of the authors, as young and possibly naïve early-career hydrogeologists, it is suggested that this overall question is one "future of hydrogeology", like the other futures of hydrogeology described in the *Hydrogeology Journal* special edition of 2005 (Voss 2005). In the following, this vast question is tentatively divided into a series of smaller questions. Undoubtedly, other researchers will raise other questions or suggest other angles or avenues of research. The purpose of this essay is to encourage this discussion.

The term "return" is used to reflect the historical trends in hydrogeologic research. In Fig. 1, the evolution of hydrogeologic research has been divided into three overlapping phases, based on trends in citations and benchmark papers (Schwartz et al. 2005; Anderson 2008). Prominent research in early quantitative hydrogeology focused on questions of "capacity" or "safe yield" when studying aquifers (Meinzer 1923; Theis 1935, 1940). Over the past ~30–40 years, the community has been largely focused on issues of groundwater contamination and quality as well as more recently on groundwater/surface-water interactions. This research remains important and can be integrated into a holistic view of groundwater and sustainability. The trajectory of hydrogeology research has been increasing in scope, interdisciplinarity and complexity (Fig. 1). It is suggested that a return to groundwater quantity research at the mega-scale, which addresses long-term issues of sustainability, equity, ecology and economics, may have a high return-on-investment for science and society.

Here, the focus is on groundwater systems at regional (≈10-km length scale) to continental (>1000 km) scales, herein called "mega-scale". Since the 1970s, hydrogeology has often, but not exclusively, focused on site-scale (<1 km) research to examine important water resource and contamination problems and how groundwater interacts with surface water. Regional-scale groundwater systems were first modeled in the 1960s (Tóth 1963; Freeze and Witherspoon 1967; Garven 1995; Person et al. 1996) but the numerical simulation of groundwater systems over entire continents has only been recently possible (Fan et al. 2007; Lemieux et al. 2008). Additionally, continental-scale remote sensing from the GRACE satellites have only recently documented real-time groundwater depletion at the mega-scale.

Numerous fundamental questions of the spatio-temporal variability of groundwater fluxes and stores remain, especially at the mega-scale. These questions resemble recurring issues in groundwater science and engineering but with a new large-scale twist:

1. What is the spatial distribution and global sum of stored fresh, uncontaminated groundwater? Answering this question necessitates an understanding of porosity and

Received: 6 February 2013 / Accepted: 7 May 2013
Published online: 28 June 2013

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 DOI 10.1007/s10040-013-0998-8

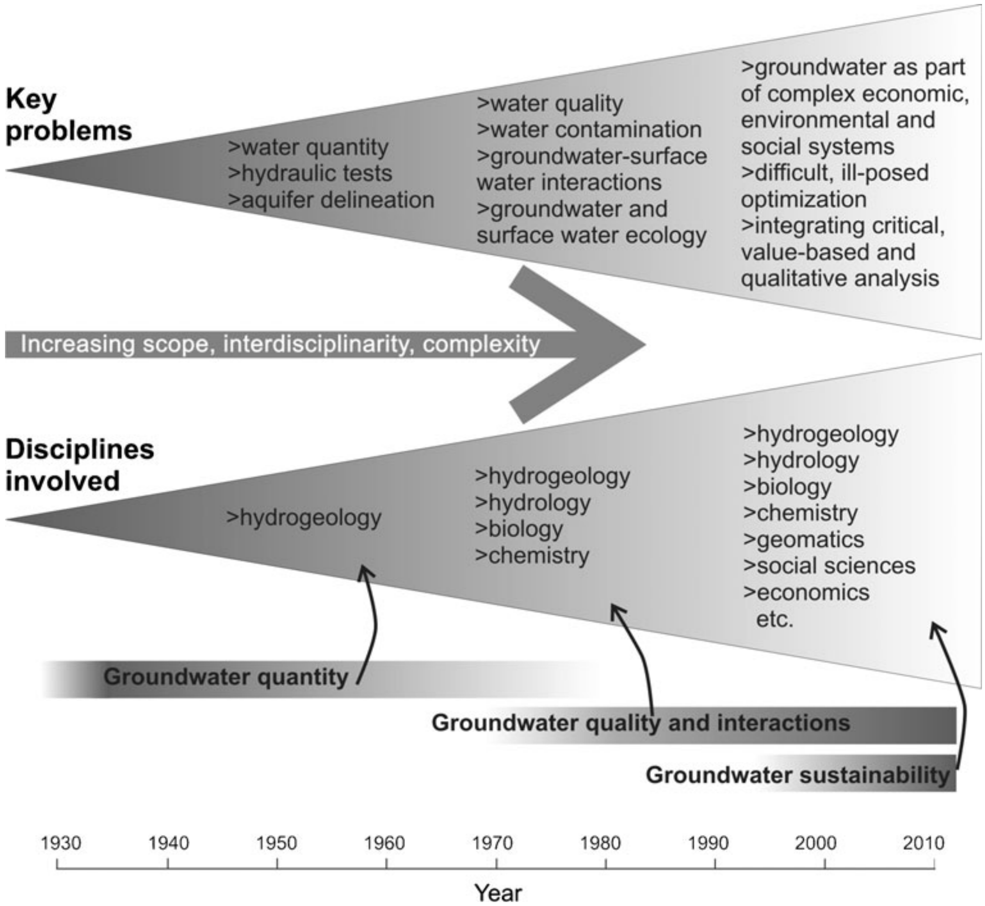

Fig. 1 The evolution of hydrogeology can be divided into three periods with increasing scope, interdisciplinarity and complexity. Time is shown roughly for each period at the bottom, based on trends in citations and benchmark papers (Schwartz et al. 2005; Anderson 2008)

compressibility at the mega-scale as well as mapping the depth of the fresh-brine interface and the spatial distribution of persistent point and non-point source contaminants.

2. How do we accurately quantify inputs and outputs of a mega-scale groundwater system?

    a. Can we more accurately determine the global spatial distribution of extraction which is currently based on heterogeneous, and often incomplete, national databases (Siebert et al. 2010)? Can extraction be defined at the scale of state or province globally or at more local scales using spatial algorithms?
    b. What is the spatial distribution of input fluxes (localised recharge, distributed recharge, artificial recharge)?
    c. What is the spatial distribution of natural output fluxes or groundwater discharge? Can we consistently define the complexities of hyporheic exchange at mega-scales (Wörman et al. 2007)?

3. How is the reversibility of storage capacity affected by long-term drawdown and subsidence at the mega-scale?
4. How do properties and processes of flow upscale over very large scales, at which it is likely that fine-scale variability can not be practically modeled?
5. How can we bridge the gap between continental-scale data (e.g. GRACE) and site-scale data such as pumping tests?
6. How do we obtain good data that reduce uncertainty of storages and fluxes in large-scale aquifers?
7. How can we more robustly incorporate a dynamic water table or groundwater/surface-water interactions into global-scale hydrologic models?
8. Can we improve techniques for model calibration and prediction at the mega-scale?

However, considering mega-scale groundwater quantity studies must also involve study of numerous other important cogs in the hydrologic machinery, which may not be amenable to study using only the standard tools in a hydrogeologists' toolbox (Fig. 1). These questions will require greater collaboration and an extension of the standard hydrogeologic thinking.

9. How will human-induced changes (land cover, extraction, etc.) affect hydrogeologic fluxes and stores over large time and space scales?
10. When and to what extent do changing hydrogeologic flows impact natural ecological systems and/or ecosystem services?
11. How will the economics of water (and concomitant energy usage) evolve in a basin undergoing development, in response to the dropping of water tables, increased contamination, and reduced hydroecologic flows?

 DOI 10.1007/s10040-013-0998-8

Some of these are fundamental process-based questions, others involve significant data synthesis, and finally others require deep interdisciplinary collaboration, new instruments or new methods. Some of these questions are the focus of individual researchers and/or national and international initiatives such as the National Science Foundation (NSF) Earth Cube program on data synthesis, the Belmont Forum on water security and the UNESCO-IHP GRAPHIC Programme (Groundwater Resources Assessment under the Pressures of Humanity & Climate Change). Together these questions represent crucial and exciting possibilities for future research that examines the large, complex and interdisciplinary questions of groundwater quantity—a timely set of subjects for a water-stressed world.

Acknowledgements This essay was significantly improved by suggestions from M. Sophocleous, S. Gorelick, L. Smith, S. Loheide and G. Ferguson and originally inspired by conversations at the 'Cutting Edge' Early Career Geoscientist workshop in June 2012 College of William and Mary, Williamsburg, VA. The workshop is sponsored by the National Association of Geoscience Teachers (NAGT) with funding provided by the National Science Foundation Division of Undergraduate Education. We thank the workshop leaders, NAGT and NSF for this opportunity and encourage other early career hydrogeologists to check out future workshops.

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DOI 10.1007/s10040-013-0998-8