Groundwater: State of the Science and Practice

Groundwater Sustainability

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Introduction

Sustainability is a wide-ranging term that can be applied to almost all aspects of life on Earth, from the local to a global scale. The National Ground Water Association (NGWA) defines groundwater sustainability as "development and use of groundwater resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental or socioeconomic consequences"—a definition adopted from the U.S. Geological Survey (Alley et al. 1999). The concept of sustainability as applied to groundwater has evolved considerably from early safe yield concepts toward a more integrated outlook (Alley and Leake 2004).

Groundwater sustainability is not a scientific concept, but rather a perspective that can frame scientific analysis. Ideally, sustainability is a vision that develops from stakeholders about what level of change caused by pumping is acceptable. The concept of sustainability presents a challenge to hydrologists to translate complex and sometimes vague socioeconomic and political questions into technical questions that can be quantified systematically. The sustainability of groundwater resources may be greatly influenced by management practices, such as managed aquifer recharge. This critical topic is covered in a separate chapter of this eBook.

Groundwater developments exist in a continuum (Pierce et al. 2013). At one extreme of the continuum are developments that can be maintained indefinitely. At the other extreme are those that are clearly mining the resource. The discussions about sustainability fall in the intermediate interval of this continuum, where one is trying to safely develop the groundwater resource for long-term use. Sustainability has many facets. This chapter looks at its connection to the evolving concept of groundwater governance and some key aspects of addressing the time response of groundwater systems.

Groundwater Governance

Recent years have seen considerable interest in promoting responsible collective action by the many people and agencies involved in groundwater—including well owners, public agencies, the private sector, environmental groups, and water consumers. These ideas fall under the general umbrella of "groundwater governance" (Foster and Garduño 2013; Megdal et al. 2015; Global Environment Facility et al. 2016). Governance differs from management in that the latter is what agencies do within the governance framework to implement the policies and plans that have been established.

Effective groundwater governance requires collaboration, meaningful stakeholder participation, and community engagement. A widely-shared understanding of groundwater systems and communication to stakeholders about how critical factors affect groundwater sustainability are also key. The greatest shortcoming of groundwater governance has been called "its failure to grasp the central importance of the human dimension . . . and the consequent neglect of stakeholders in governance and management" (Global Environment Facility et al. 2016).

Raising awareness is essential to get political and stakeholder participation, and to achieve a greater sense of urgency to address current problems and long-term risks. Rather than starting from scratch, discussions of groundwater sustainability can often build on existing frameworks, such as river basin commissions (e.g., the Delaware and Susquehanna Rivers).

A recent novel approach toward groundwater sustainability is California's Sustainable Groundwater Management Act (SGMA). Groundwater governance issues play a very large role in SGMA. For each basin defined as medium or high priority by the state, the act requires new local agencies to self-organize as groundwater sustainability agencies and develop plans to bring the basin into sustainability by about 2040. SGMA defines sustainable groundwater management as a basin operated in such a way so as not to cause "undesirable results," such as chronic depletion of groundwater, seawater intrusion, or land subsidence. Kiparsky et al. (2017) describe some of the institutional challenges.

Based on a review of nine case studies in six states, Babbitt et al. (2018) emphasize the importance of building trust, having sufficient data, using a portfolio of management approaches, assuring performance, and access to funding. After reviewing numerous examples internationally, Alley and Alley (2017) identify 13 factors contributing to good groundwater governance (see Table 1). Among these, they emphasize that the primary solutions are found at the aquifer, watershed, or local level. There's virtually no possibility of getting entrenched groundwater users on board, if they aren't actively involved in the decision-making process. At the same time, an external force is often required to achieve necessary changes and accountability.

Sustainability, Governance, and Time

Managing groundwater resources sustainably requires considering the timescales of the consequences. Society is poorly adapted to balancing environmental issues and economic development over intergenerational timescales, yet these are the timescales of many groundwater systems. Gleeson et al. (2012) suggest setting groundwater sustainability goals for many aquifers on a multigenerational time horizon (50 to 100 years), while continuing to acknowledge longer-term impacts. A key benefit of setting longer groundwater policy horizons is the educational value in fostering increased awareness of the long-term effects of pumping.

Among the most challenging aspects are those associated with capture (defined as the decrease in discharge plus the increase in recharge resulting from groundwater withdrawals). Capture is often considered synonymous with (or dominated by) streamflow depletion (Barlow and Leake 2012). It also manifests as reduced groundwater discharge to (or induced infiltration from) lakes, wetlands, and other surface water bodies, as well as reduced transpiration from groundwater.

In some areas, capture can include increased recharge caused by water-table declines in areas

Table 1. Factors contributing to good groundwater governance (from Alley and Alley 2017).

- Recognizing surface water and groundwater as a single resource
- Active engagement of local stakeholders in the decision-making process
- Pressure from external bodies to achieve suitable and workable solutions
- Public education on groundwater and its importance
- An emphasis on public guardianship and collective responsibility
- Consideration of groundwater within other policy areas, such as agriculture, energy, and land use
- Adequate laws and enforcement
- Fully funded and properly staffed groundwater management agencies
- Characterization of major aquifer systems
- Effective and independent monitoring of groundwater status and trends
- Recognizing the long-term response of groundwater systems
- Accounting for interactions between groundwater and climate
- Community leadership

where high water tables previously precluded infiltration. By examining numerous groundwater modeling studies, Konikow and Leake (2014) found that on average about 85 percent of the water pumped in these systems came from capture and 15 percent from storage depletion. The significance of capture relative to storage depletion comes as a surprise to most people.

Groundwater modeling is an essential tool to estimate how capture plays out over time and is also an example of the previous statement by the Global Environment Facility about the neglect of the human dimension in groundwater governance and management. In the past, groundwater models have been developed largely or exclusively by a single group, with limited input from those who have a stake in the outcome. A peer review generally occurs at the end of the model construction process. This has led to models with limited buy-in from stakeholders, undermining their usefulness.

It is increasingly recognized that to build trust in contentious situations, models should be developed through a more collaborative, inclusive, and transparent process with major stakeholder groups more actively involved in groundwater model development. In this way, stakeholders more fully understand the purpose of using a model, the data used in its construction, and model limitations and uncertainties. While the process requires greater commitment of time and resources, the model is much more likely to be trusted by the majority of stakeholders. Recent examples of collaborative modeling include the Upper San Pedro River in Arizona (Richter et al. 2014) and the Wood River in Idaho (Wylie 2017).

Climate is another temporal issue associated with groundwater sustainability, commonly connected with the concept of resilience (Foster and MacDonald 2014). NGWA defines resilience as the capacity of a groundwater (or water-resources) system to withstand either short-term shocks (e.g., drought) or longer-term change (e.g., climate change). When discussing resilience, the timeframe under consideration should be defined. Resilience applies to both water quantity and quality.

Climate variability and change influences groundwater systems both directly through replenishment by recharge and indirectly through changes in groundwater withdrawals. These relations can be complex (Taylor et al. 2013). Groundwater is commonly taken for granted as a buffer storage that can assure water availability during times of drought. The reality can be quite different, however, with groundwater management failing to adequately consider the natural cycles of wet years and dry years, let alone potential long-term climate change. As a result, groundwater may fail to meet its expected role in drought mitigation and droughts simply intensify the overexploitation of groundwater resources.

Key challenges in good groundwater governance are maintaining awareness during wet periods of the importance of groundwater as a backup resource, and working toward laws, regulations, and incentives that encourage use of surface water during wet periods and prepare for increased groundwater use during droughts (Alley 2016).

Final Thoughts

The long timescales and uncertainties of groundwater systems suggest the use of adaptive management approaches. Adaptive management or staged decision-making is commonly presented as an approach to making choices about long-term management under uncertainty. Although the effectiveness of adaptive management for addressing groundwater depletion remains largely untested, and if misapplied may become a rationale for early inaction (Bredehoeft and Alley 2014), setting interim short-term and long-term goals with planned revisits is an obvious need in many situations. With large uncertainties, long timeframes, and numerous stakeholders, a key challenge is to get started as soon as possible.

REFERENCES

Alley, W.M. 2016. Drought-proofing groundwater. *Groundwater* 54, no. 3: 309.

Alley, W.M., and R. Alley. 2017. *High and Dry: Meeting the Challenges of the World's Growing Dependence on Groundwater*. New Haven, Connecticut: Yale University Press.

Alley, W.M., and S.A. Leake. 2004. The journey from safe yield to sustainability. *Ground Water* 42, no. 1: 12-16.

Alley, W.M., T.E. Reilly, and O.L. Franke. 1999, Sustainability of ground-water resources. U.S. Geological Survey Circular 1186.

Babbitt, C., and seven others. 2018. *The Future of Groundwater in California: Lessons in Sustainable Management from Across the West*. Environmental Defense Fund and Daugherty Water for Food Global Institute at the University of Nebraska.

Barlow, P.M., and S.A. Leake. 2012. Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow. U.S. Geological Survey Circular 1376.

Bredehoeft, J.D., and W.M. Alley. 2014. Mining groundwater for sustained yield. *The Bridge* 44, no. 1: 33-41.

Foster, S., and H. Garduño. 2013. Groundwater-resource governance: Are governments and stakeholders responding to the challenge? *Hydrogeology Journal* 21, no. 2: 317-320.

Foster, S., and A. MacDonald. 2014. The 'water security' dialogue: Why it needs to be better informed about groundwater. *Hydrogeology Journal* 22, no. 7: 1489-1492.

Gleeson, T., W.M. Alley, D.M. Allen, M.A. Sophocleous, Y. Zhou, M. Taniguchi, and J. VanderSteen. 2012. Towards sustainable groundwater use: Setting long-term goals, backcasting, and managing adaptively. *Ground Water* 50, no. 1: 19-26.

Global Environment Facility, World Bank, UNESCO-IHP, FAO, and IAH. 2016. *Global Diagnostic on Groundwater Governance*. Groundwater Governance, A Global Framework for Action. http://www.groundwatergovernance.org (accessed July 2016).

Kiparsky, M., A. Milman, D. Owen, and A.T. Fisher. 2017. The importance of institutional design for distributed local-level governance of groundwater: The case of California's Sustainable Groundwater Management Act. *Water* 9, no. 10: 755.

Konikow L.F., and S.A. Leake. 2014. Depletion and capture: Revisiting 'the source of water derived from wells'. *Groundwater* 52**,** no. Supplemental 1: 100-111.

Megdal, S.B., A.K. Gerlak, R.G. Varady, and L-Y. Huang. 2015. Groundwater governance in the United States: Common priorities and challenges. *Groundwater* 53, no. 5: 677-684.

Pierce, S.A., J.M. Sharpe Jr., J.H.A. Guillaume, R.E. Mace, and D.J. Eaton. 2013. Aquifer-yield continuum as a guide and topology for science-based groundwater management. *Hydrogeology Journal* 21, no. 2: 331-340.

Richter, H.E., B. Gungle, L.J. Lacher, D.S. Turner, and B.M. Bushman. 2014. Development of a shared vision for groundwater management to protect and sustain baseflows of the Upper San Pedro River, Arizona, USA. *Water* 6: 2519-2538.

Taylor, R.G., and 25 others. 2013. Ground water and climate change. *Nature Climate Change* 3, no. 4: 322-329.

Wylie, A. 2017. Groundwater flow model of the Wood River Valley aquifer. Presentation at 2017 Groundwater Foundation National Conference, Boise, Idaho.