ground water

Issue Paper/

Towards Sustainable Groundwater Use: Setting Long-Term Goals, Backcasting, and Managing Adaptively

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Abstract

The sustainability of crucial earth resources, such as groundwater, is a critical issue. We consider groundwater sustainability a value-driven process of intra- and intergenerational equity that balances the environment, society, and economy. Synthesizing hydrogeological science and current sustainability concepts, we emphasize three sustainability approaches: setting multigenerational sustainability goals, backcasting, and managing adaptively. As most aquifer problems are long-term problems, we propose that multigenerational goals (50 to 100 years) for water quantity and quality that acknowledge the connections between groundwater, surface water, and ecosystems be set for many aquifers. The goals should be set by a watershed- or aquifer-based community in an inclusive and participatory manner. Policies for shorter time horizons should be developed by backcasting, and measures implemented through adaptive management to achieve the long-term goals. Two case histories illustrate the importance and complexity of a multigenerational perspective and adaptive management. These approaches could transform aquifer depletion and contamination to more sustainable groundwater use, providing groundwater for current and future generations while protecting ecological integrity and resilience.

Introduction

The sustainable use of groundwater is a crucial and significant societal challenge (Alley et al. 1999; Hiscock et al. 2002; Council of Canadian Academies 2009). Groundwater is a primary source of drinking water for as many as 2 billion people (Morris et al. 2003) and it plays a central role in irrigated agriculture (Foster and Chilton 2003; Shah 2007; Giordano 2009) and in the health of many ecosystems (Alley et al. 2002; Sophocleous 2002). Yet groundwater is often not adequately managed to ensure its long-term sustainability (Giordano 2009; Sophocleous 2010). Indeed, groundwater depletion and contamination are widespread in both developed and developing countries (Danielopol et al. 2003; Foster and Chilton 2003; Brunner and Kinzelbach 2005; Konikow and Kendy 2005; Fogg and LaBolle 2006; Rodell et al. 2009) and have locally led to significant socioeconomic impacts (Shah 2007).

Groundwater sustainability is difficult due to the long timescales of groundwater processes and impacts (Bredehoeft 2002; Michael and Voss 2008; Bredehoeft

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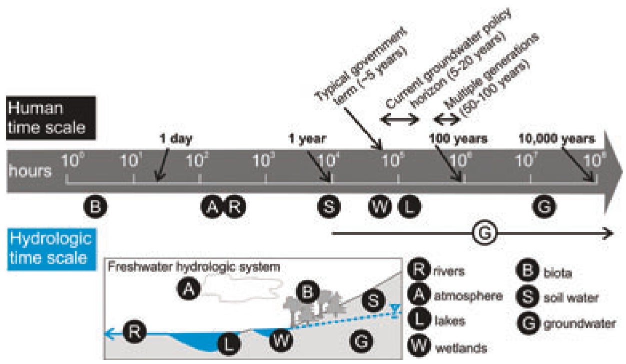

Figure 1. Comparing human and hydrologic time scales. Global mean residence times shown as black circles for freshwater in biota (B), the atmosphere (A), rivers (R), soils (S), wetlands (W), lakes (L), and groundwater (G) estimated from a world water balance (UNESCO 1978). The global mean residence time of groundwater is approximately 1400 years, distinctly longer than that of other freshwater stocks but comparable to the residence time of water in glaciers, permafrost, and the oceans (not shown). The range of groundwater ages in individual aquifers, represented by the (G) in the white circle, is large.

Table 1
Groundwater Sustainability Priorities (Downing 1998; Alley et al. 1999)

Sustainable long-term yields from aquifers
Effective use of the large volume of water stored in aquifers
Preservation of groundwater quality
Preservation of the aquatic environment by prudent development of groundwater
Integration of groundwater and surface water into a comprehensive water and environmental management system

and Durbin 2009; Narasimhan 2010; Walton 2011), and depends on how we use, manage, and value groundwater. At a global scale, mean residence times of groundwater are much longer than the residence times of other parts of the hydrologic cycle (Figure 1; UNESCO 1978). For individual aquifers, groundwater mean residence times cover a wide spectrum from <10 years to >1,000,000 years (McMahon et al. accepted). However, groundwater policy horizons are often inconsistent with natural groundwater time scales, an obstacle for long-term groundwater sustainability. Groundwater policy horizons are typically 5 to 20 years; an example is the European Union Water Framework Directive with a planning and implementation cycle of 15 years (EU 2000). The often short-term measures in groundwater management plans may not lead to long-term groundwater sustainability. Additionally, "fossil" groundwater is often unsustainably mined as a nonrenewable resource (Foster and Loucks 2006). Where groundwater is renewed rapidly, aquifers are particularly susceptible to anthropogenic contamination which can have long-term impacts (Fogg and LaBolle 2006).

Our vision for groundwater sustainability synthesizes hydrogeological science and current sustainability concepts. We consider groundwater sustainability a value-driven process of intra- and intergenerational equity that balances the environment, society, and economy. This approach is consistent with previous priorities for groundwater sustainability (Table 1; Gupta and Onta 1997; Downing 1998; Alley et al. 1999), the general understanding of sustainability (World Commission on the Environment and Development 1987; Hiscock et al. 2002; McMichael et al. 2003; Robinson 2004; Kates et al. 2005; Norton 2005), and the emerging concept of water security (World Water Forum 2000). This definition of groundwater sustainability differs significantly from the twentieth-century concept of "safe yield" which often focuses on aquifers as value-neutral physical systems (Sophocleous 2000; Alley and Leake 2004). Gleeson et al. (2010) highlighted groundwater quantity issues in fossil aquifers and suggested managing groundwater over multi-generational time horizons with community involvement and a different socioeconomic value of groundwater. We expand their arguments by also examining aquifers with short mean residence time as well as both groundwater quality and quantity issues. We emphasize three practical approaches for groundwater sustainability: setting long-term sustainability goals, backcasting, and management that is integrated, adaptive, inclusive, and local. We illustrate the importance, applicability, and challenges of these concepts with two case histories, the Abbotsford-Sumas, and High Plains aquifers.

Setting Sustainability Goals, Backcasting, and Managing Adaptively

Impacts of aquifer depletion and groundwater contamination are often only observed after long periods of time. Likewise, renewal of a depleted aquifer and remediation of contaminated groundwater may demand measures over several generations. Therefore, we suggest setting groundwater sustainability goals for many aquifers on a multigenerational time horizon (50 to 100 years) while acknowledging longer term impacts (Figure 2). Alternatively, the mean residence time or the time needed to reach a new steady state (as predicted by a calibrated groundwater model) could be used for the time horizon for setting sustainability goals, although this is normally much longer than realistic planning horizons. Mean residence times are a useful indicator of planning horizons because the mean residence time of an aquifer, defined as the average time for groundwater to flow from recharge to discharge areas, is an approximation of the aquifer renewal time (Kazemi et al. 2006). For groundwater systems with short mean residence time, the mean residence time can be used directly or as starting point for discussion of the planning horizon. For groundwater systems with long mean residence time, cyclic planning with adaptive management should be used to achieve the long-term sustainability goals.

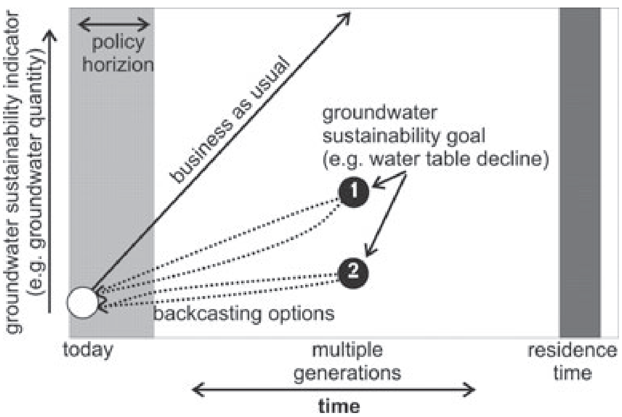

Figure 2. Groundwater sustainability goals (represented by black circles with (1) greater or (2) lesser impact on the aquifer) are set on a multigenerational time horizon (50 to 100 years) while acknowledging longer term impacts. Policies can be developed by backcasting from policy goals to policy time horizon (<50 years). Multiple backcasting options for each sustainability goal are depicted. Also shown is a business-as-usual scenario where groundwater sustainability goals are not set.

Setting goals over multigenerational time horizons is starting to be implemented. For example, the Texas Water Development Board requires groundwater management areas to set goals on 50-year time horizons (Hutchison 2010). But generally, a multigenerational policy horizon is much longer than most current groundwater policy horizons. Specific sustainability goals (represented by black circles in Figure 2) can be set for water quantity and quality as relating to the health of human and ecosystem that acknowledges the connections between groundwater, surface water, and ecosystems. Goals could include hydrogeological (e.g., water table elevations), hydrological (e.g., stream low flows), water quality, and/or ecological or human health criteria that must be maintained or achieved over a specified time horizon. Goals could also be set using aggregate groundwater indicators (Webb et al. 2006; Steinman et al. 2011). Specific policies can be developed by backcasting (Robinson 1988) from the sustainability goal to determine policies and actions that are necessary, feasible or desirable in the given policy time horizon to meet multigenerational goals (Figure 2). Backcasting starts with defining a desirable future (i.e., groundwater sustainability goal) and then works backward to identify policies and programs that will connect that future to the present. The fundamental backcasting question is "What actions must be taken to achieve a certain groundwater sustainability goal?" Conversely, forecasting predicts the future based on current trend analysis, shown by the business-as-usual line on Figure 2. Backcasting can be part of the "soft water path" (Brandes and Brooks 2006), an alternative conceptualization of water resources proposed by Gleick (2003), based on soft energy paths (Lovins 1977). Backcasting is increasingly used in surface water resource planning by a variety of jurisdictions, including the Capital Regional District in British Columbia, Canada (Brandes and Brooks 2006). The Texas Water Development Board has implemented a form of backcasting using groundwater models (Hutchison 2010). Sustainability goals, called "desired future conditions" in this case, are defined for specific conditions such as groundwater level, groundwater storage volume, or spring flow. Then groundwater models are used to estimate the maximum pumping rates that will result in the desired sustainability goal. An example of the type of model output that is useful for backcasting is shown in Figure 3 (Lavigne et al. 2010a, 2010b). Lavigne et al. (2010b) used a calibrated steady-state model of the Chateauguay River aquifer, Canada, to test the impact of hypothetical scenarios of future groundwater consumption on aquifer conditions such as drawdown or natural discharge to surface waters. Model simulation results were used to define first-order cause-effect relationships between pumping rate, drawdown, and natural groundwater discharge (Figure 3). Using these relationships, water managers and stakeholders can determine the desired sustainability goals and backcast to the present day to determine sustainable extraction rates.

Managing groundwater over multigenerational timescales necessitates a shift toward management that is integrated, adaptive, inclusive, and local. Integrated

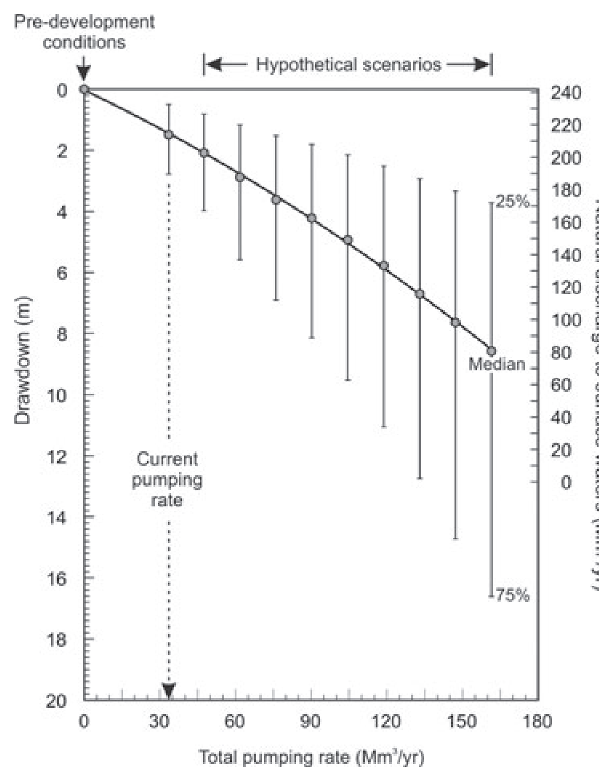

Figure 3. Simulated impacts of groundwater withdrawal scenarios for the Chateauguay River aquifers [modified from Lavigne et al. (2010b) and used with permission of the *Canadian Water Resources Journal*]. The long-term impacts of groundwater withdrawal on drawdown (left axis) and natural groundwater discharge (right axis) for nine hypothetical scenarios are shown along with current and predevelopment conditions. The points show the median drawdown and discharge values, while the bars span the 25th to the 75th percentiles.

water resource management (Jewitt 2002) is critical for managing groundwater and surface water as a single resource (Winter et al. 1998). Michigan's Water Withdrawal Assessment Tool is an example of a science-based, integrated, and local management tool to maintain streamflow-dependent aquatic and riparian ecosystem health. The tool is a groundwater model coupled to surface water and fish-response models (Steinman et al. 2011). Stakeholders first agree on sustainability goals, the allowable impacts to fish communities in different types of streams. Then, water use applicants estimate the impacts of their proposed pumping using the online tool (www.miwwat.org) as well as the cumulative impacts of all upstream withdrawals, on the nearest stream segment. If the tool indicates that the fish community in that segment would degrade past the stakeholder-set threshold, then the new water use is not permitted.

Adaptive management to changing conditions (e.g., population growth, cultural or climate change, better theory or understanding, new measurements) allows for more resilient long-term management and potentially provides a bridge within and across generations for addressing the longer term issues of groundwater sustainability. Fundamental principles of adaptive management are experimentalism and monitoring (Norton 2005). Experiments of management policies and actions could be simulated with a transient groundwater model. The model simulation should be sufficiently long to evaluate the experimental measures in achieving the long-term goals. Because model prediction is always uncertain, monitoring is essential to ascertain the effectives of the adaptive measures.

Inclusive and local (aquifer- or watershed-based) communities should set specific goals which is critical for common-pool resources such as groundwater (Ostrom 1990; Sophocleous, 2010; Theesfeld, 2010). Community participation is integral to ensure quality decisions, as the maintenance of quality depends on open dialog among all those affected (Funtowicz and Ravetz 1994). Long-term monitoring and experimentation should be embedded in a community-based and accessible framework that integrates a variety of data and modeling information. For example, farmers are measuring water table depth, rainfall, and groundwater extraction as part of a voluntary and collaborative project in Andhra Pradesh, India (Grimond 2010). They develop a water table budget and then agree on water allocations and agricultural plans. The details of the agreement are displayed publicly and updated annually with new information about rain, harvests, and revenues. In order to be part of inclusive and democratic community decisions, hydrogeologists and policy makers have to be aware of the limitations of science and be comfortable with risk, uncertainty and intuition (Norton 2005; Kelly and Farahbakhsh 2008).

Case Histories

Setting multigenerational sustainability goals and backcasting has not been systematically applied to any aquifers to our best knowledge, aside from the aquifers in Texas. The Texas Water Development Board Program is difficult to evaluate because goals have been set very recently (Hutchison 2010). Therefore, this section describes the perils of not setting long-term sustainability goals, thereby highlighting the critical importance of the approaches described in the previous section for two aquifers with very different residence times. The Abbotsford-Sumas aquifer contains predominantly modern groundwater, with groundwater ages ranging from 0.9 to 32.9 years (Wassenaar et al. 2006). Most of the groundwater in the High Plains aquifer is premodern with groundwater ages at the base of the aquifer ranging from 3400 to 15,600 years (McMahon et al. 2004a, 2004b, 2007; Gurdak et al. 2009). The case histories illustrate the importance and complexities of starting early with a multigenerational perspective, and using adaptive, inclusive, and local management.

Abbotsford-Sumas Aquifer

The Abbotsford-Sumas aquifer became the focus of public concern in the mid-1980s due to the widespread nitrate contamination problem, the detection of agricultural pesticides, and increased pressures for urban development above the aquifer (Liebscher et al. 1992; Wassenaar 1995; Zebarth et al. 1998; Hii et al. 1999; Mitchell et al. 2003). This 161 km^2 transboundary aquifer is highly productive and provides water supply for approximately 100,000 people in British Columbia, Canada, and approximately 10,000 people in northern Washington, USA. High annual recharge rate (>1 m/year) limits the effects of groundwater pumping, except in localized areas around major production wells (Scibek and Allen 2005), but the aquifer is extremely susceptible to surface-derived contamination because of its largely unconfined nature and highly permeable sands and gravels. Nitrogen, phosphorus, and potassium application on agricultural land exceeds the crop requirements by a significant margin (~40% of the area received surplus nitrogen applications in excess of 200 kg/ha/year in the late 1990s) (Schreier et al. 1999). In 1992, best management practices were recommended: reducing the amount of manure retained in the region and using synthetic fertilizer; synthetic fertilizers were thought less likely to result in nitrate contamination if application rates were controlled. Greater than 90% of farms complied with these recommendations but the production of manure increased as farming intensified across the region (Schreier, personal communication 2010). Elevated NO_3 concentrations persist in groundwater and surface water in the region (Hii et al. 2005). Thus, there is a question as to how effective best management practices set in 1992 might be at reducing nitrate loading, which underscores the importance of adaptive management and setting sustainability goals instead of only establishing best management practices.

Over the past decade, university-government partnerships have aimed to better understand linkages between climate, land use practices, groundwater processes, and nitrogen loading. Recent nitrogen isotope studies suggest the source of nitrate has shifted from manure sources to inorganic fertilizer sources which is consistent with best management practices introduced in the early 1990s (Wassenaar et al. 2006). Unfortunately, persistently high nitrate concentrations suggest that the best management practices are not having the desired effect in terms of lowering concentrations. For best management practices implemented in 1992 (~19 years ago), the effects would be detectable at depths of about approximately 14 m below the water table as groundwater age varies roughly linearly with depth (Chesnaux et al. accepted). For deeper portions of the aquifer, it would take decades to see any effect. Age dates in this aquifer provide critical insight into the timescales needed for management and monitoring. Despite introducing best management practices in the 1990s, establishing an International Task Force comprised of stakeholders from federal, provincial and state agencies, local government, nongovernmental organizations, and aboriginal and tribal groups, implementing monitoring programs, and undertaking various research projects, the primary goal of reducing agricultural contamination has not been met. Sustainability goals for this aquifer must be defined (i.e., lowering nitrate concentrations to below the drinking water limit across the aquifer) and specific policies and actions developed by backcasting from this goal. However, any actions taken now will likely take two or more decades to see any significant effect on drinking water quality. The complexities of monitoring a large, heterogeneous aquifer and the evolving scientific understanding (i.e., synthetic fertilizers were not thought to cause nitrate contamination problems in this aquifer in the early 1990s) demand an adaptive approach for water and nutrient management.

High Plains Aquifer

The fate of the High Plains aquifer, popularly known as the Ogallala aquifer, has been in the radar screen of policy analysts since at least the 1970s when significant depletion became apparent. This unconfined sand, silt, clay, and gravel aquifer system (Weeks et al., 1998; Dennehy et al. 2002) is the most intensively used aquifer in the United States and 97% of the groundwater withdrawn from the High Plains aquifer is used for irrigation (Gurdak et al. 2009). Groundwater usage is greater than recharge, resulting in groundwater mining, water table decline across broad areas (Weeks et al. 1998; Sophocleous 2010) and elimination of baseflow to many streams (Sophocleous 2000, 2003). Sophocleous (2010) summarized the current complex, multistate management of the High Plains aquifer. One of the most comprehensive water policy analyses conducted on the High Plains region today was the one commissioned by the U.S. Department of Commerce and U.S. Congress and completed in 1982 (HPA 1982). A linear-programming model was developed for each of a number of subregions in the High Plains aquifer area based on differences in soils, hydrology, and policies implemented by local or state government regarding well spacing and pumping (Buller 1982). The model was designed to maximize farm returns for each subregion by selecting the area of irrigated and nonirrigated crops, type of irrigation system, energy source, and amount of water applied per unit area under various production situations (Peterson and Bernardo 2003). Several scenarios were addressed in the study, including a baseline scenario (continuation of existing trends in water and agricultural management at the time) as well as alternative scenarios involving mandatory and/or voluntary conservation of water, water supply augmentation, and interstate surface-water transfers. A key prediction was that irrigated area would decline from approximately 0.88 million ha in 1977 (the base year) to 0.31 million ha in 2000, whereas the nonirrigated area would increase from approximately 1.61 million ha to more than 2.44 million ha based on a large projected increase in natural gas price, as nearly 80% of the irrigation systems in western Kansas were powered using natural gas (Buller 1982; HPA 1982). However, energy costs actually fell in real terms since 1977 and the actual irrigated area, instead of decreasing as predicted, increased to 0.94 million ha, and the nonirrigated area increased less than projected to 1.71 million ha in 2000 (Peterson and Bernardo 2003). In addition, the linear-programming model failed to predict the observed changes in the mixture of both irrigated and nonirrigated crops as an increasing percentage of irrigated area has been planted with water-intensive crops (corn and alfalfa) instead of less-water-demanding alternatives such as wheat, sorghum, and soybeans (Peterson and Bernardo 2003). Despite the large increases in irrigated area and production of the more water-intensive crops of corn and alfalfa, both the per-unit area water use and total water use declined over a 20-year retrospective since completion of the study as a result of increased irrigation efficiency (Peterson and Bernardo 2003). Differences in observed and projected results were attributed to a variety of factors, including large differences in crop prices, yield trends, energy prices, farm commodity programs, and irrigation technologies relative to those assumed in the study (Peterson and Bernardo 2003). The difference between predicted and actual outcomes underscores the importance of adaptive, integrated management to better account for these factors in guiding management policies, as all of these socioeconomic and agricultural changes affect the sustainability of the groundwater resource. Like the Abbotsford-Sumas aquifer, extensive research and monitoring programs focus on the High Plains aquifer, yet the primary goal of reducing depletion remains largely elusive. Sustainability goals for this aquifer must be defined (i.e., stopping or lowering the rate of water table decline) and specific policies and actions developed by backcasting from this goal.

Discussion: Towards Sustainable Groundwater Use

Can groundwater use be sustainable? We think groundwater sustainability is possible but not without a significant transformation of how we value and manage groundwater resources, and how we monitor and characterize hydrogeological systems. This will not be simple or straightforward because of the number of stakeholders, the necessity of cooperation across jurisdictions, and our often myopic political and economic systems. But we have already experimented with the other possibility: short-term groundwater policy that has led to widespread aquifer depletion and contamination. The two case histories have commonalities but also highlight that a universal definition and process for achieving groundwater sustainability are not likely possible (Brunner and Kinzelbach 2005). Commonalities include the importance of long-term goals and adaptive management as well as the potential role of backcasting. In both cases, setting long-term goals and backcasting decades ago could have enabled more sustainable groundwater use. Hydrogeologists played critical roles in both case histories by modeling and monitoring the aquifers as well as examining the fundamental hydrogeological processes such as recharge or nitrate transport. Also in both cases, long-term plans or predictions proved inaccurate due to evolving scientific understanding (i.e., nitrate source in the case of the Abbotsford-Sumas aquifer) or socioeconomic conditions (i.e., natural gas prices in the case of the High Plains aquifer), underscoring the necessity of malleable, adaptive management. We believe that the solutions to both groundwater quantity and quality issues should be developed inclusively and locally. Aquifer-based communities can implement policy to achieve multigenerational goals that can later be modified using adaptive management. In the short-term, defining locally relevant goals and values and locally changing groundwater usage and protection will be critical. Hydrogeologists can play an active role by using groundwater models to simulate effects of management polices and measures in achieving the long-term sustainable goals and by monitoring the effectiveness of polices and measures. Information from modeling and monitoring provides scientific basis for adapting management measures. Water managers, local communities, and hydrogeologists should work together to set long-term goals, to device polices and measures by backcasting, and to adapt future measures in achieving the long-term sustainable goals. This is a feasible path towards sustainable groundwater use.

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