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TRACKING U.S. GROUNDWATER

RESERVES FOR THE FUTURE?

BY WILLIAM M. ALLEY

During the past 50 years, groundwater depletion has spread from isolated pockets to large areas in many countries throughout the world. Groundwater occurs almost everywhere beneath the land surface. Its widespread occurrence is a major reason it is used as a source of water supply worldwide. Moreover, groundwater plays a crucial role in sustaining streamflow between precipitation events and especially during protracted dry periods. In addition to human uses, many plants and aquatic animals are dependent upon groundwater discharge to streams, lakes, and wetlands.

A growing awareness of groundwater as a critical natural resource leads to some basic questions. How much groundwater do we have left? Are we running out? Where are groundwater resources most stressed? Where are they most available for future supply? To address these basic and seemingly simple questions requires consideration of several complexities of defining groundwater availability and a review of how one monitors groundwater reserves.

The term "groundwater reserves" is used to emphasize the fact that groundwater, like other limited natural resources, can be depleted. This potential for depletion is a key concept, despite the fact that unlike nonrenewable resources such as mineral deposits, most groundwater resources are replenished. On the other hand, some "fossil" groundwaters in arid and semiarid areas have accumulated over tens of thousand of years (often under cooler, wetter climatic conditions) and are effectively nonrenewable except by artificial recharge of surface water or treated wastewater.

Groundwater management decisions in the United States are made at a local level, which may be a state, municipality, or special district formed for groundwater management. Thus, monitoring of groundwater reserves should be designed to provide the information needed by these entities as a primary consideration. The issues to be addressed are varied and occur at many scales from preservation of a small spring fed by a nearby water source to the management of groundwater development throughout a large aquifer system or river basin.

The nation's groundwater reserve is not a single vast pool of underground water, but rather is contained within a variety of aquifer systems.[1] In general, the locations of the nation's aquifers are known, so much of the current research focuses on characterizing aquifer systems and how they respond to human activities.[2]

Many aquifers cross political divides, including county, state, and international boundaries. This characteristic (as well as the specialized nature of the science of groundwater hydrology) drives the need for a federal role and multijurisdictional collaboration in groundwater monitoring. Concerns about groundwater reserves have become more regional, national, and even global in scale in recent years, as exemplified by interstate and international conflicts over the salinization, contamination, or overexploitation of groundwater.[3] The effects of groundwater development may require many years to become evident. Thus, there is an unfortunate tendency to forgo the data collection and analysis that is needed to support informed decisionmaking until after problems materialize.

How Much Groundwater Is Available?

The volume of water stored as groundwater is often compared to other major global pools of water within the Earth's hydrological cycle. For example, if one ignores water frozen in glaciers and polar ice, groundwater comprises more than 95 percent of the world's freshwater resources. This statistic illustrates the considerable value of groundwater, but it is also misleading, as it misses the variation in quantity, quality, and availability from location to location. The volume of groundwater in storage, its quality, and the yield to wells vary greatly across the planet. Typically, groundwater is used locally, so the effects of localized pumping on a given region are the primary concern of hydrogeologists.

Estimates of the volume of groundwater are poorly known relative to other pools of water. For example, the volume of the Earth's oceans has been well known for many years, whereas global estimates for groundwater storage vary by orders of magnitude (see Table 1 on this page). In part, this variability is due to different considerations of depth and salinity in defining the global groundwater pool. In addition, the variability reflects less knowledge about groundwater than other

Table 1. Volume of water attributed to oceans and groundwater over time

	Cubic kilometers of water (in thousands)	
Date	**Oceans**	**Groundwater**
1945	1,372,000	250
1967	1,320,000	8,350
1978	1,338,000	10,530–23,400
1979	1,370,000	4,000–60,000
1997	1,350,000	15,300

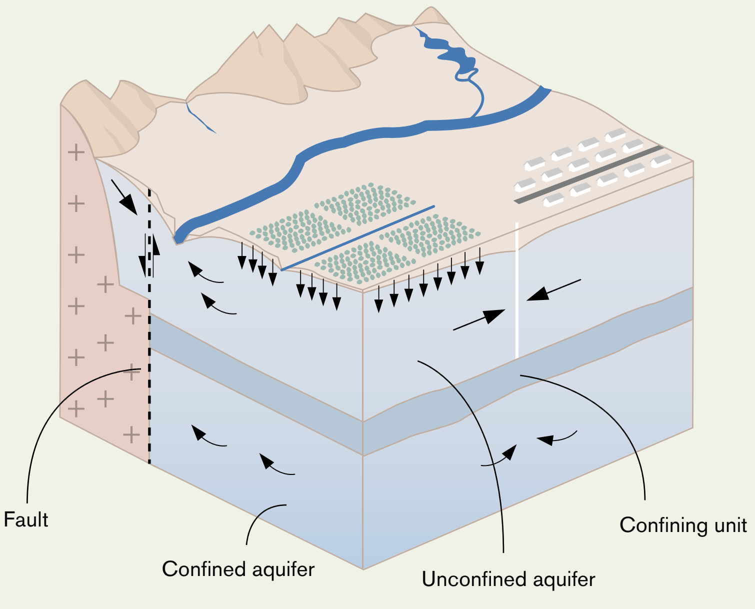
NOTE: These data come from different studies of the world water balance. Significant figures are largely retained from original sources.

SOURCE: W. M. Alley, J. W. LaBaugh, and T. E. Reilly, "Groundwater as an Element in the Hydrological Cycle," in M. Anderson, ed., *The Encyclopedia of Hydrological Sciences* (Chichester, UK: John Wiley and Sons Ltd., 2005), 2215–28.

global pools of water. Early estimates of the global groundwater pool greatly underestimated its volume. It was not until after development began in earnest in the mid-twentieth century that an appreciation of the large storage volume of groundwater emerged universally. More recently, scientists have viewed this resource as an important component of the world water cycle and have expressed increasing interest in quantifying its role.[4]

As a practical matter, it is virtually impossible to remove all water from storage with pumping wells. However, the volume of recoverable groundwater in storage for a particular area or aquifer can be estimated as the product of the area, saturated thickness, and specific yield (accounting as appropriate for differences in the estimates of saturated thickness and specific yield among multiple layers or zones).[5] To assess the value and limitations of estimates of groundwater in storage, it is helpful to first consider how aquifers are drained and then look at their dynamic links to the surface environment.

Figure 1. Hypothetical basin-fill aquifer system



NOTE: The arrows show the direction of groundwater flow. Among the features shown are an unconfined aquifer overlying a confining unit and confined aquifer, a gaining stream, recharge from irrigated agriculture, and mountain-front recharge.

SOURCE: Modified from S. A. Leake, *Modeling Ground-Water Flow with MODFLOW and Related Programs,* U.S. Geological Survey Fact Sheet, 121–97 (Washington, DC, 1997).

Aquifer Drainage

The mechanism of aquifer drainage depends on whether an aquifer is unconfined or confined (see Figure 1 on this page). In an unconfined aquifer, the upper surface of the saturated zone (water table) is free to rise and decline. The principal source of water from pumping an unconfined aquifer is the dewatering of the aquifer material by gravity drainage. The volume of water that is usable in practice is limited by the aquifer's permeability (how easily water moves through a rock unit), water quality, cost of drilling wells, and design of the well and pump.

Consider as an example the unconfined High Plains aquifer, which underlies an area stretching from southern South Dakota to the end of the panhandle of Texas and is the most heavily pumped aquifer in the United States. Depletion of aquifer storage from pumping has had substantial effects on irrigated agriculture in the High Plains, particularly in the southern half, where more than 50 percent of the saturated thickness has been dewatered in some areas. In Kansas, scientists have estimated the lifespan of the aquifer by projecting past trends into the future until the saturated thickness of the aquifer reaches a level at which groundwater pumping for irrigation becomes impractical.[6] The results suggest that many areas in western Kansas have less than 50 years of usable groundwater remaining. Thirty feet of saturated thickness was the critical level in this study, although the researchers noted additional studies that suggest that 30 feet is not enough saturated thickness to provide sufficient well yields for irrigation.

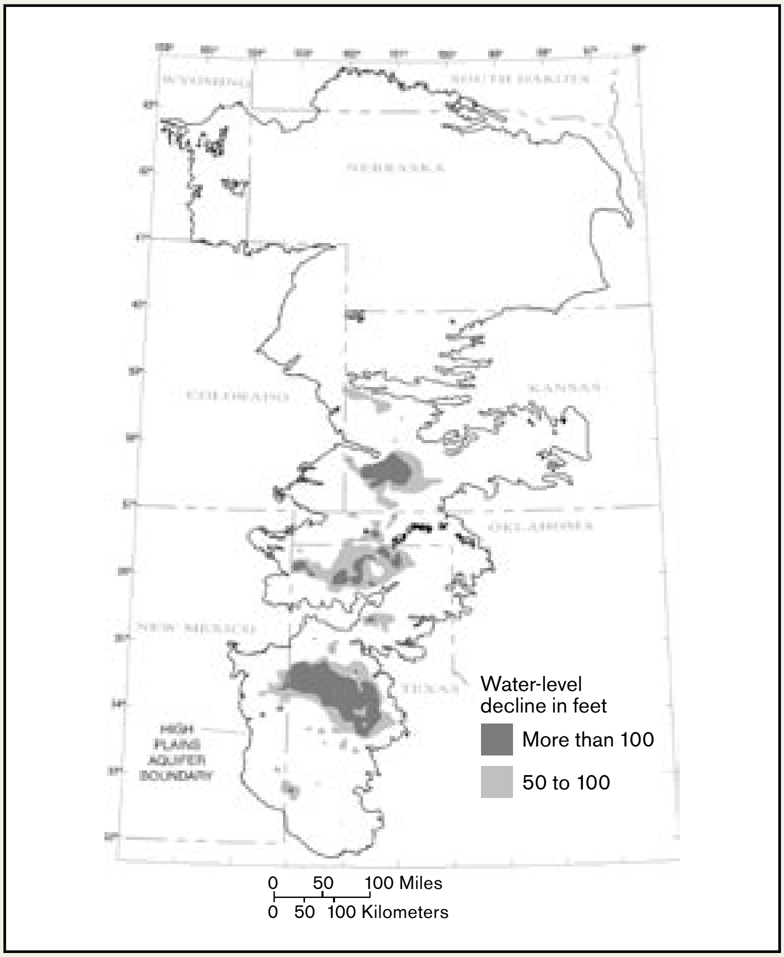
Changes in groundwater levels throughout the High Plains aquifer are tracked annually through the cooperative effort of the U.S. Geological Survey and state and local agencies in the High Plains region (see Figure 2a on page 14). Despite the considerable effects of storage depletion in much of the High Plains, only 6 percent of the volume of water in the High Plains aquifer has been depleted since pumping began (see Figure 2b on page 15), illustrating how aggregated information about storage depletion over large areas can mask significant local effects.

Confined aquifers, which underlie low permeability confining systems, are filled by water under pressure and respond to pumping differently. The water for pumping is derived not from pore drainage but rather from aquifer compression and water expansion as the hydraulic pressure is reduced. Pumping from confined aquifers results in more rapid water-level declines covering much larger areas when compared to pumping the same quantity of water from unconfined aquifers. If water levels in an area are reduced to the point where an aquifer changes from a confined to an unconfined condition (becomes dewatered), the source of water becomes gravity drainage as in an unconfined aquifer. A major complication arises, however, because the drawdowns in the confined aquifer will induce leakage from adjacent confining units. Slow leakage over large areas can result in the confining unit supplying much, if not most, of the water derived from pumping.[7] Therefore, it is particularly difficult to relate estimates of the volume of groundwater in storage to the usable volume of groundwater in confined aquifers.

Further complications may arise for those aquifers with silt and clay layers that can permanently compact as a result of pumping. Consider, for example, the Central Valley aquifer in California, the nation's second-most-pumped aquifer. By 1977, about 28 percent of the decrease in aquifer storage of 60 million acre-feet was the result of permanent reduction of pore space by compaction, resulting in land subsidence throughout much of the area.[8] Farmers in the Central Valley have drawn on imported surface water as a major source of irrigation water to reduce groundwater depletion and associated subsidence. The decrease in aquifer storage of 60 million acre-feet, although very large, represented only a small part of the more than 800 million acre-feet of freshwater stored in the upper 1,000 feet of sediments in the Central Valley.[9]

Similarly, subsidence caused by groundwater pumping in the low-lying coastal environment of Houston, Texas,

Figure 2a. Changes in groundwater levels in the High Plains aquifer from predevelopment to 2000



SOURCE: V. L. McGuire et al., *Water in Storage and Approaches to Ground-Water Management, High Plains Aquifer, 2000*, U.S. Geological Survey Circular 1243 (Reston, VA, 2003).

has increased its vulnerability to flooding and tidal surges. As a result, Houston has undertaken an expensive shift from sole reliance on its vast groundwater resource to partial reliance on surface water for its water supply.

Several key points arise from the examples and discussion thus far. First, measurement of storage depletion should be placed in the context of individual aquifer systems. For example, in evaluating water-level declines, one has to distinguish carefully between confined and unconfined aquifers, as the two respond very differently to pumping. Second, aquifer-wide estimates of recoverable water in storage have limited utility without considering the distribution of water-level changes and their effects. Finally, depletion of a small part of the total volume of water in storage can have substantial effects that become the limiting factors to development of the groundwater resource. These issues are further reinforced when one considers the response of surface-water bodies to groundwater pumping.

Interactions with Surface Water

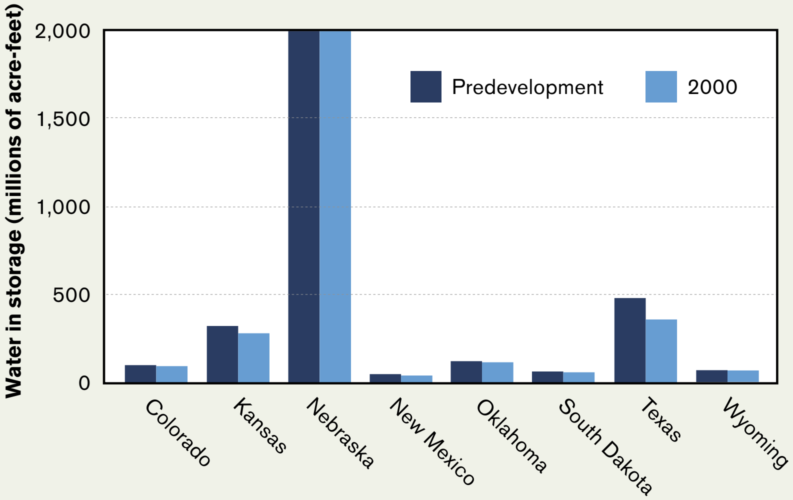
Groundwater flows from areas of recharge to areas of discharge. Recharge includes water that naturally enters a groundwater system and water that enters the system at artificial recharge facilities or as a consequence of human activities such as irrigation and waste disposal. Discharge may occur to the atmosphere by transpiration; to streams, lakes, and other surface-water bodies; or through a pumping well. The balance between groundwater recharge and discharge controls groundwater levels and storage in a manner analogous to how deposits and withdrawals control savings in a bank account. If recharge exceeds discharge for some period, groundwater levels and storage will increase. Conversely, groundwater levels and storage will decline during periods when discharge exceeds recharge.

A common misperception is that the development of a groundwater system is "safe" if the average rate of groundwater withdrawal does not exceed the average annual rate of natural recharge. People sometimes make the erroneous assumption that natural recharge is equivalent to the basin sustainable yield.[10] Even further misinterpretations suggest that pumping at less than the recharge rate will not cause water levels and groundwater storage to decline.

To understand the fallacy inherent in these conclusions, one needs to consider how groundwater systems respond to pumping. Under natural conditions, a groundwater system is in long-term equilibrium. That is, averaged over some period (and in the absence of climate change), the amount of water recharging the system is approximately equal to the amount of water leaving (discharging from) the system. Withdrawal of groundwater by pumping changes the natural flow system, and the water is supplied by some combination of increased recharge, decreased discharge, and removal of water that was stored in the system.

Initially, water levels in pumping wells will decline to induce the flow of water to these wells, and water is removed from storage. Subsequently, the groundwater system readjusts to the pumping stress by "capturing" recharge or discharge. Also, the storage contribution to the water budget decreases with time for any given

Figure 2b. Comparison of predevelopment and 2000 groundwater in storage by state



SOURCE: V. L. McGuire et al., *Water in Storage and Approaches to Ground-Water Management, High Plains Aquifer, 2000*, U.S. Geological Survey Circular 1243 (Reston, VA, 2003).

withdrawal. If the system can come to a new equilibrium, the changes in storage will cease (at a new reduced level of groundwater storage), and inflows will again balance outflows. Thus, the long-term source of water to discharging wells becomes a change in the inflow and outflow from the groundwater system.

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This woman measures the water level in a Colorado observation well. Over time, data from these wells can show the extent of groundwater depletion.

The amount of groundwater available for use depends upon how the changes in inflow and outflow affect the surrounding environment and upon the extent to which society is willing to accept the resultant environmental changes. Consequences include reduced availability of water to riparian and aquatic ecosystems and reduced availability of surface water for use by humans. Further complicating matters, the effects of pumping on surface-water resources can be spread out over a long period of time, as illustrated by the alluvial aquifer example in Figure 3 on page 17.

In many areas, the effects of groundwater pumping on surface-water resources, and importantly, the large uncertainties associated with these effects, become the limiting factors to groundwater development. For example, University of Arizona water law and policy expert Robert Glennon in his popular book *Water Follies* describes controversial situations from throughout the United States where groundwater pumping affects streams and lakes.[11] The effects on surface water can occur with relatively little depletion of the total amount of groundwater in storage. One of the areas Glennon discusses is the Upper San Pedro River Basin in southeastern Arizona, where concerns about streamflow depletion have caused conflicts between development and environment interests in this ecologically diverse riparian system. The health of the riparian system is dependent on the groundwater level and hydraulic gradient near the stream. A key question is how pumping in the basin affects these components of riparian system health. Congressionally mandated efforts are under way to reduce the annual storage depletion (overdraft) in the Sierra Vista area—a subwatershed of the Upper San Pedro Basin.[12] Current overdraft in the Sierra Vista subwatershed is about 10,000 acre-feet per year, which is small, relative to estimates ranging from 20 to 26 million acre-feet of total groundwater storage.[13] A monitoring plan is an important element for verifying the effectiveness of management measures in reducing overdraft in the Sierra Vista subwatershed, with the ultimate goal of mitigating impacts on the riparian system.

Water-Quality Limitations

Groundwater contamination from human activities clearly places constraints on groundwater availability. Likewise, water-quality constraints on groundwater availability can result from pumping. Perhaps best known are the many cases of saltwater intrusion from pumping groundwater along coastal areas. Groundwater pumping also can induce movement of saline water from underlying aquifers in inland areas. Likewise, shallow polluted groundwater may be induced or accelerated downward and throughout an aquifer by prolonged pumping, such that contaminated groundwater penetrates further and more quickly than otherwise anticipated. The removal of water from storage also changes the quality of the remaining groundwater because good quality water commonly is withdrawn first, and the residual often includes poorer quality groundwater from elsewhere in the aquifer or groundwater that has leaked into the aquifer from adjacent units in response to declining water levels. All these and other possible changes in water quality need to be considered in conjunction with information about changes in water levels and water in storage in evaluating the availability of groundwater. In some cases, the quality of groundwater will be suitable for some uses but not others. Water treatment may be necessary to meet some needs.

Groundwater Use

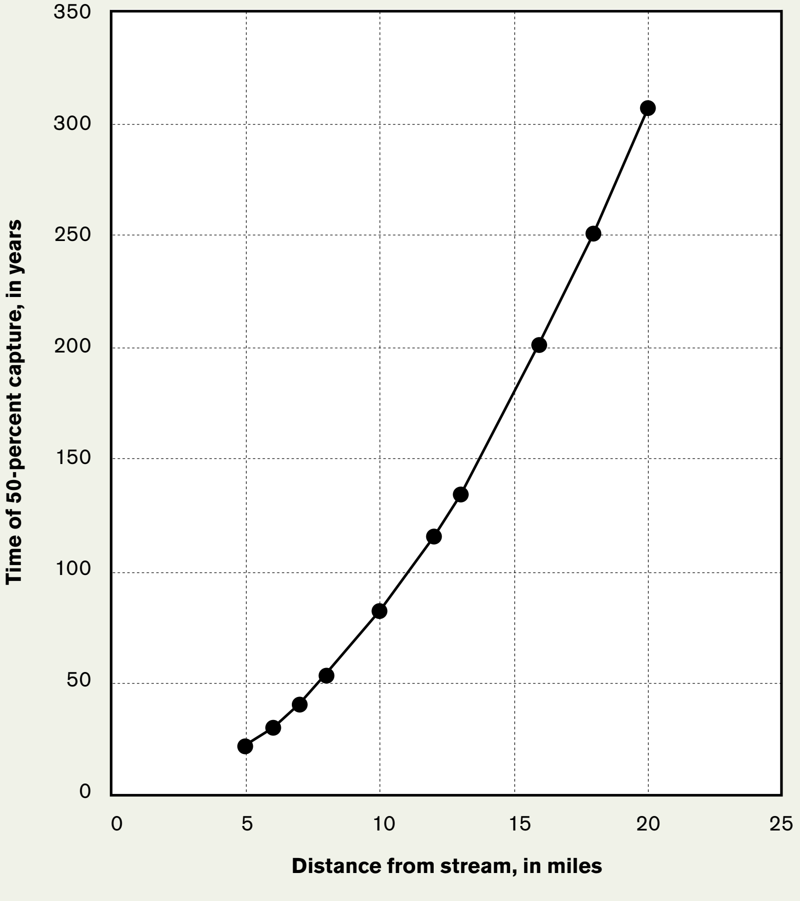
An average of 85 billion gallons of groundwater are withdrawn daily in the United States. More than 90 percent of these withdrawals are used for irrigation, public supply (deliveries to homes, businesses, industry), and self-supplied industrial uses. Irrigation is the largest use, accounting for about two-thirds of the amount. The percentage of total irrigation withdrawals provided by groundwater increased from 23 percent in 1950 to 42 percent in 2000. Groundwater provides about half the nation's drinking water with nearly all those in rural areas reliant upon groundwater.[14]

The importance of groundwater withdrawals in the United States is similar to that in the rest of the world, with some variations from country to country. Rapid expansion in groundwater use occurred between 1950 and 1975 in many industrial nations and subsequently in much of the developing world. The intensive use of groundwater for irrigation in arid and semi-arid countries has been called a "silent revolution" as millions of independent farmers worldwide have chosen to become increasingly dependent on the reliability of groundwater resources, reaping abundant social and economic benefits but with limited management controls by government water agencies.[15] Perhaps as many as two billion people worldwide depend directly upon groundwater for drinking water. (For more about international reliance on groundwater, see the article by Franklin M. Fisher, beginning on page 26.) The dependence on groundwater for drinking water is particularly high in Europe, where about 75 percent of the drinking-water supply is obtained from groundwater.[16]

Water-use data, when coupled with a scientific understanding of how aquifers respond to withdrawals, are crucial for water planning. Yet information on groundwater use is spotty and often inaccurate within the United States and worldwide. In the United States, practices for collecting water-use data vary significantly from state to state and from one water-use category to another, in response to laws regulating water use and interest in water-use data as an input for water management. Programs to collect water-use data in each state are summarized in a review by the National Research Council.[17]

Some water-use data, such as withdrawals for drinking water and other household uses and withdrawals by some industrial users are obtained by direct measurement, and some may be estimated as the amount reported or allowed by permit. Many uses, such as for self-supplied domestic use, agriculture, and some indus-

Figure 3. Effect of pumping on surface-water resources



NOTE: Time of 50-percent capture is the number of years until 50 percent of the pumping rate is accounted for as reduced groundwater discharge to the stream. The relation is for a fully penetrating stream in an aquifer having a transmissivity to storage ratio of 110,000 square feet per day.

SOURCE: C. Fillippone and S. A. Leake, "Time Scales in the Sustainable Management of Water Resources," *Southwest Hydrology* 4, no. 1 (2005): 17.

tries, are often estimated using coefficients relating water use to another characteristic, such as number of employees, number of units manufactured, irrigated acreage, or number of livestock. For example, self-supplied domestic water withdrawals are typically determined by multiplying an estimate of the self-supplied population by a per-capita use coefficient. Likewise, water use for a particular type of industry might be estimated using information on employment or production and estimates of gallons per day per employee or per unit of product. Ideally, coefficients used for water-use estimation are grounded in representative data records. In practice, they are often derived empirically or developed using data that are sparsely sampled in time and space and perhaps extrapolated beyond the climatic, technological, and economic conditions for which they were originally developed. Other complications arise in these calculations because it may be difficult to separate surface-water and groundwater withdrawals without site-specific data and because small-scale use may be excluded from official statistics.

In determining the effects of pumping, it is important to recognize that not all the water pumped is necessarily consumed. For example, some of the water pumped for irrigation is lost to evapotranspiration, and some of the water returns to the groundwater system by infiltration, canal leakage, and other paths of irrigation return flow. Of course, water that is not used for consumption can undergo substantial changes in quality between withdrawal and recharge. Ideally, information on groundwater use includes estimates of consumptive use and return flow as well as withdrawals.

Groundwater Sustainability and Management

Achieving an acceptable tradeoff between groundwater use and the long-term effects of that use is a central theme in the evolving concept of groundwater sustainability.[18] Initially, people viewed groundwater as a convenient resource for general use, and they focused their attention on the economic aspects of groundwater development. Sustainability concerns, emerging in the early 1980s, have brought environmental viewpoints and an intergenerational perspective to the forefront in discussions about groundwater availability.

Groundwater sustainability is commonly defined in a broad context as the development and use of groundwater resources in a manner that can be maintained for an indefinite amount of time without causing unacceptable environmental, economic, or social consequences. The amount of time it takes for the effects of pumping to be manifested elsewhere in the environment reinforces the importance of sustainability as a concept for groundwater management but also makes sustainable solutions difficult to apply in practice. Application of sustainability concepts to water resources requires that the effects of many different human activities on water resources and the overall environment be understood and quantified to the greatest extent possible over the long term. Thus, sustainability likely requires an iterative process of continued monitoring, analysis, application of management practices, and revision. For some cases, particularly in arid areas, the groundwater resource is treated as nonsustainable.[19]

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A man waters a golf course with a powerful hose. How much water will we pump from groundwater reserves before we implement new strategies to monitor and conserve them?

The tradeoff between the water used for consumption and the effects of groundwater withdrawals—on maintenance of instream-flow requirements for fish and other aquatic species, the health of riparian and wetland areas, and other environmental needs—is the driving force behind discussions about the sustainability of many groundwater systems. Considerable scientific uncertainty is associated with disputes over whether pumping will have a specific impact on a particular river or spring. Further complicating matters is the fact that although they are linked through the hydrologic cycle, groundwater and surface water are typically managed separately under different laws and administrative bodies.

Groundwater management strategies are composed of a small number of general approaches:[20]

- use of sources of water other than local groundwater, by shifting the local source of water (either completely or in part) from groundwater to surface water or importing water from outside the local water-system boundaries (the California Central Valley and Houston have implemented these approaches);
- changing rates or spatial patterns of groundwater pumping to minimize existing or potential unwanted effects (examples include moving well fields inland to avoid saltwater intrusion, shifting from deep to shallow groundwater or vice versa, and maintaining sufficient distances between wells to avoid excessive drawdown);
- control or regulation of groundwater pumping through implementation of guidelines, policies, taxes, or regulations by water management authorities (these imposed actions may include restrictions on some types of water use, limits on withdrawal volumes, or establishment of critical levels for aquifer hydraulic heads);
- artificial recharge through the deliberate introduction of local or imported surface water—whether potable, reclaimed, or waste-stream discharge—into the subsurface for purposes of augmenting or restoring the quantity of water stored in developed aquifers (options include infiltration from engineered impoundments, direct-well injection, and pumping designed to induce inflow of freshwater from surface waterways);
- use of groundwater and surface water through the coordinated and integrated use of the two sources to ensure optimum long-term economic and social benefits;
- conservation practices, techniques, and technologies that improve the efficiency of water use, often accompanied by public education programs on water conservation;
- reuse of wastewater (gray water) and treated wastewater (reclaimed water) for non-potable purposes such as irrigation of crops, lawns, and golf courses;
- desalination of brackish groundwater or treatment of otherwise impaired groundwater to reduce dependency on fresh groundwater sources.

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Irrigation in the San Joaquin Valley in California. The water for these extensive agricultural projects comes from groundwater reserves.

These general approaches are not mutually exclusive; that is, the various approaches overlap, or the implementation of one approach will inevitably involve or cause the implementation of another. For example, many approaches involve combinations of surface water, groundwater, and artificial recharge. During periods of excess surface-water runoff, and when surface-water impoundments are at or near capacity, surplus surface water can be stored in aquifer systems through artificial recharge. Conversely, during droughts, increased groundwater pumping can be used to offset shortfalls in surface-water supplies. Depleted aquifer systems can be seen as potential subsurface reservoirs for storing surplus imported or local surface water.

It is important to frame the hydrologic implications of various alternative development strategies in such a way that their long-term implications can be properly evaluated, including effects on the water budget. For example, changing the rates or patterns of groundwater pumping will lead to changes in the spatial patterns of recharge to or discharge from groundwater systems. As another example, in some areas of extensive use of artificial recharge, such as parts of southern California, water from artificial recharge may have replaced much of the native groundwater.

Monitoring Groundwater Reserves

Water-level measurements in observation wells provide the primary source of information about groundwater reserves. Water-level data collected over periods of days to months are useful for determining an aquifer's hydraulic properties; however, data collected over years to decades are required to monitor the long-term effects of aquifer development and management.

The amount of effort in collecting long-term water-level data varies greatly from state to state, and many long-term monitoring wells are clustered in certain areas.[21] Although they are difficult to track, the number of long-term observation wells appears to be declining because of limitations in funding and human resources. For example, the number of long-term observation wells monitored by the U.S. Geological Survey (USGS) declined by about half from the 1980s to 2000.

For many decades, hydrogeologists and others have been making periodic calls for a nationwide program to obtain more systematic and comprehensive records of water levels in observation wells. O. E. Meinzer, a longtime chief of the USGS Ground Water Division and considered by many to be the father of the science of hydrogeology, described the characteristics of such a program about 70 years ago:

> *The program should cover the water-bearing formations in all sections of the country; it should include beds with water-table conditions, deep artesian aquifers, and intermediate sources; moreover, it should include areas of heavy withdrawal by pumping or artesian flow, areas which are not affected by heavy withdrawal but in which the natural conditions of intake and discharge have been affected by deforestation or breaking up of prairie land, and, so far as possible, areas that still have primeval conditions. This nation-wide program should furnish a reliable basis for periodic inventories of the ground-water resources, in order that adequate provision may be made for our future water supplies.*[22]

More recently, the Heinz Center report *The State of the Nation's Ecosystems* indicated that data on groundwater levels and rates of change are "not adequate for national reporting."[23] This report advocated supplementing existing networks to develop a national indicator of trends in groundwater levels. The U.S. Government Accountability Office noted that no federal agencies are collecting groundwater data on a national scale and only the USGS and National Park Service are collecting water-level data on a regional scale.[24]

Historically, water-level measurements were simply tabulated, recorded in a paper file, and possibly published in reports. Today, many agencies use the Internet to enhance users' access to current and historical monitoring data. Furthermore, continuous collection, processing, and transmission of water-level data on the Internet in "real time" (typically updated every few hours) is becoming more of a standard procedure. Real-time groundwater data are useful in formulating drought warnings, as they suggest potential effects on water levels in shallow domestic wells. Real-time capability can lead to improved data quality (from continual review of the data) as well as to increased interest in groundwater conditions on the part of the general public.

In addition to water-level monitoring, certain geophysical techniques can enhance the delineation and interpretation of water-level changes over a region. For example, microgravity methods can be used to measure the small gravita-

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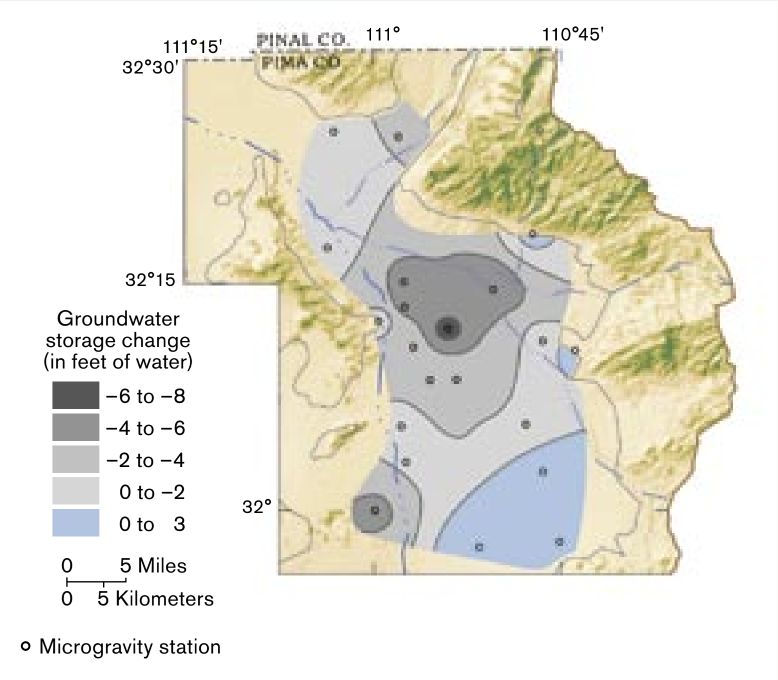
An irrigation canal in Arizona. Providing water for crops in arid, desert-like conditions requires a lot of pumping from underground sources.

tional changes that result from changes in groundwater storage (including water stored in the unsaturated zone) over an area (see Figure 4 on this page). More recently, researchers have proposed satellite-based measurements of gravity to measure changes over areas the size of a large part of the High Plains aquifer.[25] Meeting the majority of needs for water-level information requires much finer detail than that which satellite measurements can provide, but future technologies may improve this technique. Land- and satellite-based gravity measurements provide area-wide information on changes in the volume of water in storage but do not provide information on vertical changes in heads (water levels) in aquifer systems.

A second geophysical technique, Interferometric Synthetic Aperture Radar (InSAR), uses repeated radar signals from space to measure land-surface uplifts or subsidence at high degrees of measurement resolution and spatial detail.[26] Like gravity methods, InSAR has the advantage of being able to make measurements over large areas and between monitoring wells. The InSAR information can provide additional insights into the areal extent of groundwater depletion where it is linked to subsidence, and can even detect uplift from artificial recharge. InSAR has been found to be particularly useful in identifying faults and geologic structures that may impede groundwater flow and affect the response of an aquifer system to pumping.

Figure 4. Change in groundwater storage in the Tucson Basin, 1989–1998



NOTE: Change in storage was estimated usng microgravity measurements.

SOURCE: D. R. Pool, D. Winster, and K. C. Cole, *Land Subsidence and Ground-Water Storage Monitoring in the Tucson Active Management Area, Arizona*, U.S. Geological Survey Fact Sheet 084–00 (Reston, VA, 2000).

Integrated Monitoring and Assessment of Groundwater Reserves

As previously noted, the desire for a national network for monitoring groundwater levels has been discussed since the early 1900s but remains unfulfilled. Meanwhile, groundwater issues have evolved beyond early concerns focused on the hydraulics of individual wells and well field development to encompass many aspects of groundwater, including quantity, quality, and interactions with surface water. Technological advances have been made in sensors, communications, and electronic control systems to monitor groundwater, and computer modeling has become widely used to evaluate groundwater systems. From today's perspective, what might an ideal national program involve?

First and foremost, a national water-level monitoring program should be a collaborative process that involves discourse among local, state, and federal governmental agencies, nongovernmental organizations, and the public.[27] Ideally, data collected would serve double-duty by contributing to the larger regional and national picture while meeting local needs. There should be sufficient consistency in approach to describe the status of

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Groundwater depletion has caused considerable land subsidence in the San Joaquin Valley.

groundwater reserves across the country and to show how different constraints affect utilization of the nation's aquifers. A major early goal would be to identify critical gaps in existing coverage.[28]

Many of the primary issues affecting groundwater availability require analysis at the scale of aquifers to achieve a meaningful perspective. To that end, monitoring programs should be designed in the context of the specific characteristics of each aquifer system. A comprehensive national monitoring program should track major aquifers that are affected by groundwater pumping, areas of future groundwater development, and areas of groundwater recharge. Water levels should be measured in wells open to different depths and in the context of the three-dimensional groundwater-flow system.

A long-term record of water-level measurements should encompass the period between the natural and developed states of aquifer systems. Other approaches, such as gravity measurements to estimate subsurface-water storage changes, should be considered in conjunction with the water-level monitoring program. Establishing links between water-level and water-quality requires an understanding of groundwater-flow systems. Studies of natural mixing in aquifers suggest that existing damage to groundwater quality may be lasting and could gradually extend deeper into aquifer systems, thereby reducing further groundwater availability.[29]

Data on changes in groundwater levels provide essential information about changes in groundwater storage and provide the simplest way to convey the extent of groundwater depletion. However, changes in groundwater storage are only part of the story. As noted in previous examples, the status of groundwater reserves should be placed in the context of the complete water budget for that aquifer system. Thus, the monitoring of surface water and groundwater should be linked, particularly measurements of streamflow during low-flow periods when groundwater discharge is the primary component of streamflow. This might require an increase in the number of streamgaging stations in targeted basins to estimate the groundwater contribution to streamflow.

In addition to monitoring data on natural systems, estimation of water withdrawals and consumptive use is an essential part of computing a water budget for a developed aquifer system. Groundwater pumping is one component of the water budget that is physically possible to measure; yet it is commonly one of the most uncertain components of the water budget. Water-use information should be an integral part of evaluations of groundwater quantity and quality and other environmental conditions. Where multiple overlying aquifers are used, efforts should be made to estimate withdrawals from each.

Groundwater systems are dynamic and adjust over decades or more to pumping and other stresses. Many aquifer systems have undergone several decades of intensive development and may be far from equilibrium. Thus, it is challenging to place current conditions in the context of the dynamic but slow changes that may be taking place. A simple snapshot of current conditions may not indicate, for example, how future streamflow depletion will evolve from the pumping that has already occurred.

During the past several decades, computer models for simulating groundwater and surface-water systems have played an increasing role in the evaluation of groundwater development and management alternatives. Groundwater modeling serves as a quantitative means of evaluating the water balance of an aquifer, as it is affected by land use, climate, and groundwater withdrawals, and how these changes affect streamflow, lake levels, water quality, and other important variables. Generally, monitoring and computer modeling are treated as distinct activities, but to be most effective, the two should be linked. Such a framework is considered further below, and its essential elements are illustrated in Figure 5 on page 23.

Monitoring groundwater reserves serves as primary information used in the development and calibration of computer models. Likewise, the process of model calibration and use provides insights into which components of the system are best known, which components are poorly known, and which components are more important than others. Thus, the experience gained from modeling should provide a basis for a periodic evaluation of the monitoring network.

As its basis, every simulation model has a conceptual model that represents the prevailing theory of how the groundwater system works. The appropriateness of this conceptual model is tested as a numerical model is built, and field observations are compared to the model simulations. Unfortunately, more often than not, data will fit more than one conceptual model, and good calibration of a model does not ensure a correct conceptual model. Thus, conceptual and numerical modeling should be viewed as an iterative process in which the conceptual model is continuously reformulated and updated as new information is acquired.[30] The importance of this approach and its link to monitoring data is recognized explicitly in Figure 5 as a key step prior to each new stage of groundwater modeling.

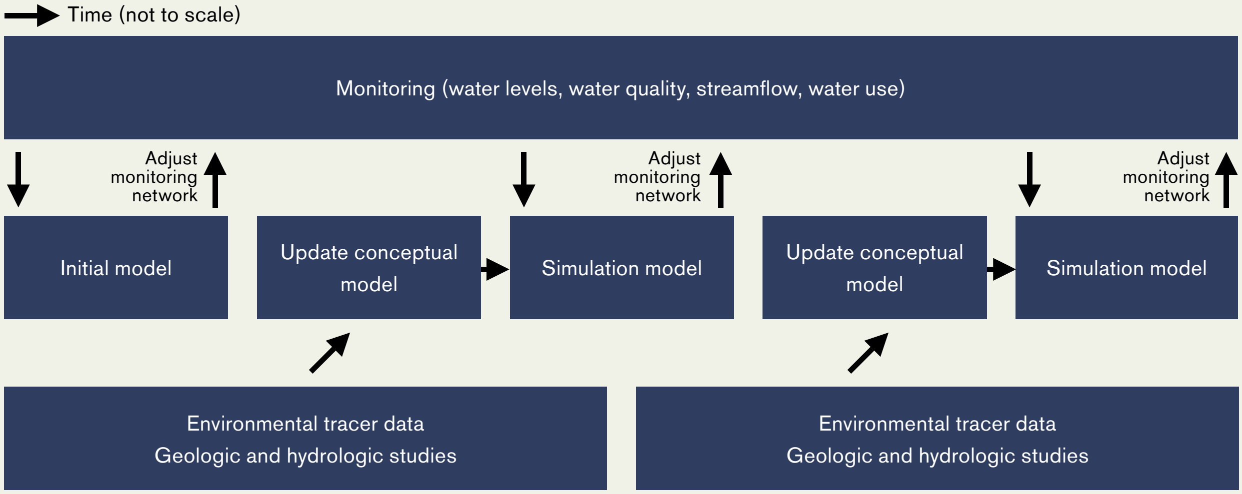
Additional scientific studies conducted at the time of modeling or during intervening periods can provide insights into the adequacy of the conceptual model that underlies the computer model as well as help in adjustment of model parameters. Such studies include use of environmental tracers, studies of the geologic framework, and geophysical studies. For example, an increasing number of chemical and isotopic substances are being measured in groundwater to identify water sources, trace directions of groundwater flow, and measure the age of the water (time since recharge). Comparison of the results from these environmental tracers with information from computer modeling can lead to either increased confidence in the conceptual model of a groundwater system or recognition of the need for changes. The Middle Rio Grande Basin in central New Mexico (see the box on page 24) provides an example of how long-term water-level monitoring combined with environmental and geologic studies has contributed to an evolving series of conceptual and simulation models used to help manage the groundwater resources of the basin.

Not all aquifer systems lend themselves to the exact same approach. For example, consolidated geological formations with fractures, joints, or solution cavities can be difficult to model, given the discontinuous nature of their permeability. These rocks commonly are highly vulnerable to contamination, and the wide range in water-level fluctuations can cause shallow domestic wells to go dry during extended droughts. Interpretation of water-level monitoring from individual wells is difficult in such terrain. It remains important, however, to have a conceptual model of the system as a driving force behind the monitoring network design with a goal to quantify that model as knowledge of the system improves.

One should not infer that the simulation model in Figure 5 is always the same. Indeed, a stepwise approach may be used in which simpler analytic codes are used in the initial phases before constructing three-dimensional numerical models. Also, it is likely that further groundwater research will develop multiple models addressing different roles and objectives. Each model provides a means to reevaluate the monitoring network from a different perspective and to advance understanding of how the water balance of the aquifer system responds to human development.

Generalized long-term monitoring will provide critical information for many uses but will not offset the need for very specific monitoring to address more localized issues, such as the effects of pumping on the ecology of a stream reach. Ideally, the

Figure 5. Tracking groundwater resources



broader scale monitoring programs provide a hydrologic context for the design of such studies.

Conclusions

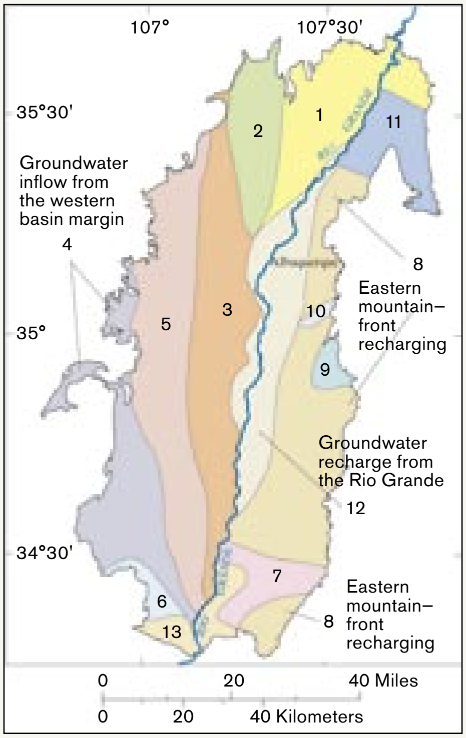
Groundwater monitoring data serve as a foundation that permits informed management decisions on many kinds of groundwater resource and sustainability issues. Unfortunately, data on groundwater conditions and trends are generally lacking worldwide: Groundwater is commonly undervalued, and there is a deceptive time lag between withdrawals and the resultant impacts of those withdrawals. Long-term groundwater data from individual wells are useful primarily as part of a broader analysis of aquifer systems; thus, the value of data from individual wells is often as invisible as the resource they represent.

Long-term water-level monitoring needs to be integrated with analysis of other monitoring data and an underlying model of the water budget of the aquifer

MIDDLE RIO GRANDE BASIN

The Middle Rio Grande Basin encompasses about 38 percent of the population of New Mexico and is the primary source of water supply to the City of Albuquerque and surrounding area. Some of the most productive parts of the aquifer system are in eastern Albuquerque, where, coincidentally, most of the initial groundwater development occurred. This led to the popular belief that the entire Middle Rio Grande Basin was underlain by a highly productive aquifer that was equivalent to one of the Great Lakes. During the 1980s and early 1990s, a combination of large water-level declines measured in monitoring wells (greater than 150 feet in some areas) and new insights into the geologic framework of the basin led to serious questions about this paradigm. In 1995, the New Mexico State Engineer declared the Middle Rio Grande Basin a "critical basin" faced with rapid economic and population growth for which there is less than adequate technical information about the available groundwater supply.

To fill some of the gaps in information, an intensive 6-year effort was undertaken to improve understanding of the hydrogeology of the basin.[1] Geological, geophysical, and environmental tracer studies provided new insights into the source areas for recharge to different parts of the aquifer; indicated that mountain-front recharge is less than previously estimated; showed that the hydraulic connection between the Rio Grande and the aquifer is less than previously thought in some areas; identified new faults that may affect groundwater flow; and suggested that the aquifer is less productive in some areas than previously thought (see the figure at right). The new information was incorporated into a revised groundwater model for the region. In conjunction with the study, new monitoring wells were established in the Albuquerque area, generally as nests of several wells completed at different depths in the aquifer and located to minimize short-term fluctuations caused by nearby high-capacity production wells. The combined approach of monitoring, modeling, and scientific studies has been instrumental in helping the City of Albuquerque revise its water-use and future water-supply strategy.



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[1] J. R. Bartolino and J. C. Cole, *Ground-Water Resources of the Middle Rio Grande Basin, New Mexico*, U.S. Geological Survey Circular 1222 (Reston, VA, 2002), http://pubs.water.usgs.gov/circ1222.

system (typically a simulation model) as a means for interpreting monitoring results and guiding the design of monitoring networks. Regular reassessment of monitoring objectives is necessary to ensure that monitoring programs provide the information needed by groundwater users and those who manage water resources. To enhance the value of groundwater data, managers and policymakers must also ensure the continuity of data-collection programs over time.

Within the United States, one might summarize the current situation as one in which we have some ability to track groundwater levels and water use for many aquifers, generally have limited ability to place these data in the context of groundwater sustainability for most aquifers, and often lack an integrated approach with feedback among monitoring, simulation, scientific studies, and management approaches. Similar issues exist in managing groundwater resources throughout the world.[31] Fortunately, the ability to access groundwater data on the Internet and to portray them in a spatial context should continue to enhance their visibility and value in the coming years.

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NOTES

1. Single geologic units may define aquifers. Alternately, multiple aquifers and surrounding lower permeability units may be collectively referred to as "aquifer systems." The two terms are used somewhat interchangeably in this article, with "aquifer systems" used when an emphasis is placed on aquifers as hydrologic systems. The *Ground Water Atlas of the United States* describes many of the important aquifers of the nation and can be found at http://capp.water.usgs.gov/gwa/.

2. W. M. Alley, R. W. Healy, J. W. LaBaugh, and T. E. Reilly, "Flow and Storage in Groundwater Systems," *Science* 296, 5575 (14 June 2002): 1985–90.

3. National Research Council, *Confronting the Nation's Water Problems: The Role of Research* (Washington, DC: National Academies Press, 2004), 187; and L. F. Konikow and E. Kendy, "Groundwater Depletion: A Global Problem," *Hydrogeology Journal* 13, no. 1 (2005): 317–20.

4. G. M. Hornberger, "A Water Cycle Initiative," *Ground Water* 43, no. 6 (2005): 771.

5. Saturated thickness is the vertical thickness of the aquifer in which the pore spaces are filled (saturated) with water. Specific yield is the ratio of the volume of water that a saturated rock will yield by gravity drainage to the volume of the rock. Specific yield typically ranges from 0.05 to 0.3.

6. B. B. Wilson, D. P. Young, and R. W. Buddemeier, *Exploring Relationships Between Water Table Elevations, Reported Water Use, and Aquifer Subunit Delineations*, Kansas Geological Survey Open File Report 2002-25D (Lawrence, KS, 2002).

7. For example, in a well-known study, researchers found that most of the water pumped from the confined Dakota sandstone aquifer in South Dakota has come from confining beds. J. D. Bredehoeft, C. E. Neuzil, and P. C. D. Milly, *Regional Flow in the Dakota Aquifer: A Study of the Role of Confining Layers*, U.S. Geological Survey Water-Supply Paper 2237 (Washington, DC, 1983).

8. G. L. Bertoldi, R. H. Johnston, and K. D. Evenson, *Ground Water in the Central Valley, California—A Summary Report*, U.S. Geological Survey Professional Paper 1401-A (Washington, DC, 1991). Land subsidence is a gradual settling or sudden sinking of the Earth's surface. Several different processes can cause it. Most water-related subsidence occurs as a result of compaction of aquifer materials (as in the Central Valley), drainage and oxidation of organic soils, and the dissolution and collapse of limestone and other susceptible rocks forming sinkholes and similar features.

9. Ibid., page 27.

10. J. D. Bredehoeft, "Safe Yield and the Water Budget Myth," *Ground Water* 35, no. 6 (1997): 929.

11. R. J. Glennon, *Water Follies: Groundwater Pumping and the Fate of America's Fresh Waters* (Washington, DC: Island Press, 2004).

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16. B. L. Morris et al., *Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management*, United Nations Environment Programme (UNEP) Early Warning and Assessment Report Series, RS 03-3 (Nairobi, Kenya, 2001).

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