# Groundwater depletion: A global problem

**Leonard F. Konikow · Eloise Kendy**

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## Introduction

In the past half-century, ready access to pumped wells has ushered in a worldwide "explosion" of groundwater development for municipal, industrial, and agricultural supplies. Globally, groundwater withdrawals total 750–800 km$^3$/year (Shah et al. 2000). Economic gains from groundwater use have been dramatic. However, in many places, groundwater reserves have been depleted to the extent that well yields have decreased, pumping costs have risen, water quality has deteriorated, aquatic ecosystems have been damaged, and land has irreversibly subsided.

Groundwater depletion is the inevitable and natural consequence of withdrawing water from an aquifer. Theis (1940) showed that pumpage is initially derived from removal of water in storage, but over time is increasingly derived from decreased discharge and/or increased recharge. When a new equilibrium is reached, no additional water is removed from storage. In cases of fossil or compacting aquifers, where recharge is either unavailable or unable to refill drained pore spaces, depletion effectively constitutes permanent groundwater mining. In renewable aquifers, depletion is indicated by persistent and substantial head declines.

Excessive groundwater depletion affects major regions of North Africa, the Middle East, South and Central Asia, North China, North America, and Australia, and localized areas throughout the world. Although the scope of the problem has not been quantified globally, on-going analysis by the senior author indicates that about 700–800 km$^3$ of groundwater has been depleted from aquifers in the US during the 20th century. One of the best documented cases is the 450,000 km$^2$ High Plains aquifer system in the central US, where the net amount of water removed from storage during the 20th century was more than 240 km$^3$—a reduction of about 6% of the predevelopment volume of water in storage (McGuire et al. 2003). In some of the most depleted areas, use of groundwater for irrigation has become impossible or cost prohibitive (Dennehy et al. 2002).

In some cases, removing the most easily recoverable fresh groundwater leaves a residual with inferior water quality. This is due, in part, to induced leakage from the land surface, confining layers, or adjacent aquifers that contain saline or contaminated water. In coastal areas, where many of the world's largest cities are located, the available volume of fresh groundwater is reduced by seawater intrusion and upconing, which in turn are caused by head declines in the aquifer.

As depletion continues worldwide, its impacts worsen, portending the need for objective analysis of the problem and its possible solutions. This essay examines future options for evaluating and managing groundwater depletion in a changing physical and social landscape.

## Quantifying the magnitude of depletion

In general, the magnitude of depletion is rarely assessed and poorly documented, particularly in developing countries and in humid climates. As a necessary precursor to addressing the problem, future efforts will be directed toward developing and refining methods of quantifying depletion.

Groundwater depletion can be viewed from two different perspectives. In one, depletion is considered literally and simply as a reduction in the volume of water in the saturated zone, regardless of water quality considerations. A second perspective views depletion as a reduction in the usable volume of fresh groundwater in storage. For example, seawater intrusion in a coastal aquifer may represent a substantial depletion with respect to water quality, but result from only a trivial depletion in the total volume of fluid in the subsurface. In either case, tracking and estimating the magnitude of depletion is not simple and straightforward, in large part due to a sparsity of relevant data on subsurface conditions and uncertainty in interpreting available data.

Some causes and impacts of groundwater depletion are neither obvious nor easy to assess. For example, groundwater pumped from confined aquifers may be largely derived from leakage from adjacent confining beds, but depletion of low-permeability layers is difficult to estimate, rarely monitored, and usually overlooked. Likewise, lowered water tables may make groundwater less available to phreatophytes and reduce groundwater discharge to springs, streams, and wetlands (Fig. 1). Where a stream is hydraulically connected to an aquifer, streamflow may be reduced by decreasing groundwater discharge into the stream and/or by inducing seepage from the stream into the aquifer. In rivers already stressed by excessive surface-water diversions, it is difficult to distinguish the component of streamflow depletion attributable to reduced baseflow from groundwater discharge.

The most direct way to estimate the volume of water depleted from an aquifer is to integrate maps of head changes over the aquifer area. The resulting aquifer volume is multiplied by an appropriate storage coefficient to compute the corresponding volume

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L. F. Konikow (✉)
U.S. Geological Survey,
431 National Center,
Reston, VA, 20192, USA
e-mail: lkonikow@usgs.gov
Tel.: +1-703-648-5878
Fax: +1-703-648-5274

E. Kendy
Kendy Hydrologic Consulting,
656 N. Ewing St., Helena, MT, 59601, USA

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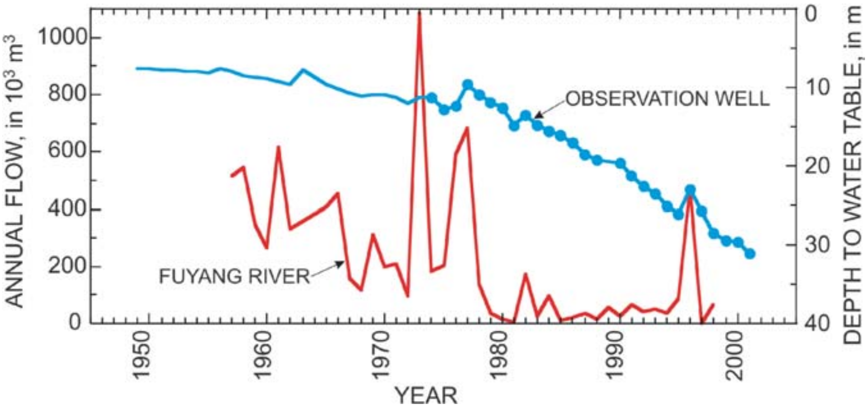


**Fig. 1** Stream and well hydrographs from North China Plain showing evidence of reduced streamflow caused by groundwater depletion (groundwater levels prior to 1974 from simulation model calibrated by Kendy 2002)

of water. McGuire et al. (2003) used this approach to estimate depletion in the High Plains aquifer in the USA. Future improvements in collection and telemetry of water-level data, data base management systems, and networking of information systems will likely make it easier to map water-level changes in the future.

Numerical simulation models commonly are used to compute water budgets of regional aquifer systems. If a model is developed using technically sound hydrogeologic judgment and is reasonably well calibrated for both predevelopment and developed conditions, then its output provides estimates of the rate of depletion. In the future, well-calibrated three-dimensional models will be available for more aquifer systems, making it easier to track and predict changes in the volume of groundwater in storage.

Land subsidence can result from irreversible compaction of low-permeability materials in or adjacent to the developed aquifer as fluid pressure declines because of groundwater withdrawals. Extensive subsidence has been well documented in Mexico City, Bangkok, Shanghai, and elsewhere. In confined aquifer systems subject to large-scale overdraft, the volume of water derived from irreversible aquitard compaction is essentially equal to the volume of land subsidence and typically can range from 10 to 30% of the total volume of water pumped (Galloway et al. 1999). Because the extent and magnitude of subsidence can be mapped accurately using a variety of techniques, the minimum magnitude of groundwater depletion can be estimated from the observed extent (and volume) of subsidence.

Although confining units are not usually envisioned as sources of groundwater supply, drawdown in aquifers induces leakage from adjacent confining units. Slow leakage over large areas can result in the confining units supplying most of the water derived from pumping a confined aquifer. For example, Bredehoeft et al. (1983) analyzed the deep, confined Dakota sandstone aquifer in South Dakota, north-central USA, and concluded that "most of the water released from storage in the system since development began has come from the confining beds." This type of groundwater depletion, which affects water quality as well as quantity, will likely garner more attention in the future.

Geophysical gravity methods offer a means to estimate changes in subsurface water storage directly by measuring changes in the Earth's gravitational field (Pool et al. 2000; Hoffman this issue). This method was applied to the Tucson Basin in southern Arizona, USA, for the period 1989–1998 (Fig. 2). In the future, sequential gravity surveys may be conducted from satellites to measure changes in groundwater storage efficiently and accurately over large regions. This technique has the potential to offer near-real-time monitoring and assessment of subsurface hydrologic changes, to which water managers can respond accordingly.

## Groundwater depletion and global climate change

Global climate change will profoundly affect hydrologic systems worldwide. Glacial melting and increasing ocean temperatures lead to sea-level rise. On the continents, the frequency and severity of floods and droughts are expected to increase, while higher temperatures will reduce winter snowpack and hasten spring snowmelt from mountainous areas. Unchecked, groundwater depletion can exacerbate the impacts of these changes; conversely, controlled management of groundwater depletion can contribute to their mitigation.

Assuming that the volume of groundwater depleted during the past 100 years is much greater than can be accounted for by non-transient increases in volumes of water stored in soil, natural channels and lakes, or the atmosphere, then the ultimate sink for the "missing" groundwater is the oceans. Worldwide, the magnitude of groundwater depletion from storage may be so large as to constitute a measurable contributor to sea-level rise. For example, the total volume depleted from the High Plains aquifer equates to about 0.75 mm, or about 0.5%, of the observed sea-level rise during the 20th century. Reducing future groundwater depletion (and increasing groundwater storage) can help in a small way to reduce future sea-level rise.

Historically, society's response to floods and droughts has been to impound surface water in reservoirs, and to release it as needed. However, a dearth of geologically suitable locations for new dams, combined with increased awareness of their ecological consequences, will hinder this response to future hydrologic extremes, even as their frequency and intensity increase. Long-term temperature rises will increase the need to store water for distribution over a longer dry season (Service 2004). In some areas, an integrated solution can be achieved by artificially recharging excess runoff, when available. Thus, depleted aquifers can be transformed into underground "reservoirs" to supplement the flood- and drought-buffering capacity of existing surface-water reservoirs.

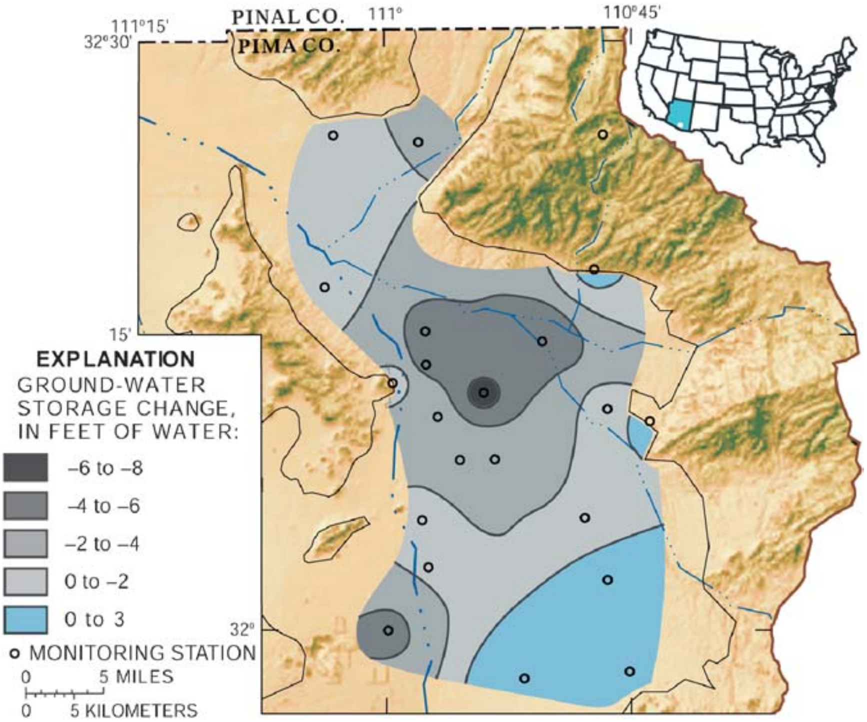
## Management solutions and challenges

Societies respond to water-resource depletion by shifting management objectives from locating and developing new supplies to augmenting, conserving, and reallocating existing supplies (Molle 2003). At the same time, societal objectives are evolving to value water for nontraditional uses, such as maintaining instream flows for aquatic ecosystems. Future groundwater management will have to address these multifaceted challenges.

*Augmenting* supplies can mean improving water quality or increasing water quantity. Depletion due to quality considerations can often be overcome by treatment, whereas large volumetric depletion can only be alleviated by decreasing discharge or increasing recharge. Artificial recharge of stormflow and treated municipal wastewater, for example, has successfully reversed groundwater declines. In the future, improved infiltration and recharge technologies will be more widely used to maximize the capture of runoff and treated wastewater.

*Conserving* groundwater by reducing pumpage can be accomplished through administrative, legislative, or management con-

**Fig. 2** Change in groundwater storage in the Tucson Basin, southern Arizona, 1989–1998, estimated using gravity methods (modified from Pool et al. 2000)



trols, including economic incentives to reduce demand. It is important to target reductions that actually save water. In agricultural areas, for example, improved efficiency is sometimes sought through lining irrigation canals to reduce seepage. But this approach saves no water if the leaky canals are themselves a major source of recharge to the underlying aquifer, as in the North China Plain (Kendy et al. 2003). If on-farm efficiency gains in saving water are used to irrigate additional land, there will be no overall reduction in water consumption.

*Reallocating* water resources will play an increasingly important role in groundwater management. Water markets, leasing, trading, and other mechanisms can move limited water from lower to higher productivity sectors, as an alternative to further depletion.

Effective reallocation requires rules to ensure fairness and minimize damages. When large-scale groundwater development began, no institutional mechanisms were in place to control the amount of withdrawals. In contrast to large-scale surface-water systems, which are centrally managed, groundwater supplies were mostly "managed" by individual users. Thus, groundwater development has been largely unregulated, even in many water-scarce areas.

Decentralized management has resulted in a lack of coordination between surface- and groundwater use, despite their vital physical connection. Efficient reallocation requires that groundwater and surface water be managed conjunctively. However, the transition to coordinated regulation can be extremely difficult, as in the Snake River basin of Idaho, northwestern US, where 750 farmers, businesses, and cities recently were ordered to shut down 1,300 wells to restore reduced spring discharge. Up to 450 km$^2$ of farms, more than 125,000 dairy cattle, several food processing plants, and 14 cities are affected (Barker 2004). In the future, as today, efforts to counter groundwater depletion will be complicated by competing demands on the resource.

Reallocation between economic sectors provides opportunities to optimize conjunctive use. Optimization methods may be used to position pumping centers to maximize withdrawals while minimizing detrimental effects such as stream depletion and well interference. This may lead future water managers to implement appropriation zoning or to require well permits in which allowable pumping rates vary with location because of hydrogeologic properties, distance from boundaries, and unit responses of surface water.

Some regions, particularly in semi-arid and arid climates, may follow the lead of Saudi Arabia, which abandoned its goal of grain self-sufficiency through irrigated agriculture when groundwater mining could not be sustained. In other areas, large-scale water transfer projects might maintain activities and populations that depend on or benefit from the depletion of groundwater resources, even at the expense of environmental impacts in the water-exporting basin.

"Virtual" water imports and exports in the form of grain represent a global response to regional groundwater depletion. For example, analyses of projected water supply and demand scenarios indicate that conventional approaches of augmenting and conserving irrigation water are insufficient to sustain agricultural water use on the North China Plain. Instead, Yang and Zehnder (2001) suggest reallocating irrigation water to urban and industrial use, retiring irrigated land, and importing grain. Ultimately, global reduction in groundwater depletion rates will likely translate to reduced crop production.

Managers of both surface and groundwater will face new challenges of fulfilling not only the traditional objectives of securing water supplies, but also of improving and protecting ecological health, while facing greater climatic fluctuations and population pressure. To achieve consensus, managers must balance the competing needs of people, industry, agriculture, and the environment. At present, many developed countries that place high value on ecological health of springs, wetlands, and streams have the ability to engineer solutions to help meet these complex challenges. In developing countries, where the livelihoods of millions of poor people may depend on unsustainable groundwater withdrawals, water managers face additional complexities that are not amenable to engineering solutions alone. In the future, the pressure of increasing populations worldwide may foster greater acceptance of groundwater depletion, regardless of a nation's development stage.

In the next few decades, groundwater depletion will likely continue to grow, but at a reduced rate. The change in trend is already in evidence in several depleted aquifers in the western US, and results in large part from positive management actions, but also to some degree from the tendency towards self-limitation of depletion imposed by hydraulic and economic constraints.

Although hydrogeologic understanding of an aquifer system is a valuable component of groundwater management, it cannot by itself define policy. DuMars and Minier (2004) argue that “only a knowledgeable, thoughtful democratic society can ultimately respond to issues of policy.” The challenge for hydrogeologists is to develop and apply innovative technical approaches, built upon a solid scientific foundation, that credibly inform society of the impacts and alternatives to groundwater depletion.

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