Global Groundwater? Issues and Solutions

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Abstract

Groundwater plays a major, if often unrecognized, role in both hydrologic and human systems. The majority of the world's drinking water probably comes from groundwater, and in the last half century, there has been an amazing, if largely ignored, boom in agricultural groundwater use that has provided improved livelihoods and food security to billions of farmers and consumers. However, increased use of groundwater has also created problems, and there are fears—sometimes challenged—that the boom may soon turn to bust. This article reviews the recent literature on the geographic and temporal dimensions of groundwater use and the range of technological and institutional approaches which have been applied in attempts at its management. It then examines the key reasons the resource has proven so difficult to manage and concludes that, in many cases, the most promising solutions may lie outside the groundwater sector and within a broader approach to resource systems.

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INTRODUCTION

The discourse on groundwater and groundwater use is focused on the language of enigma. On the supply side, groundwater is often referred to as an invisible, silent (1, 2) or hidden (3, 4) resource, whose location, quantity, and function in natural and human systems is poorly known. On the demand side, the rapid expansion in groundwater exploitation of recent decades has come to be known as a silent revolution (2), with phenomenal increases in use taking place by millions of farmers, typically investing their own private capital in drilling and pumping technologies and operating without concurrence of formal water bureaucracies.

There is no question that the use of groundwater has brought astounding benefits to literally billions of people. Probably the majority of the world's cities rely to some degree on groundwater for urban water supply, and it could be argued that groundwater in part enabled the global urbanization phenomena we are now witnessing. No less spectacularly, large-scale agricultural groundwater use has brought massive benefits to legions of small, poor (or previously poor) farmers, particularly in Asia. Although the value of groundwater use is unquestioned, the sustainability of that use is.

Groundwater tables are falling at phenomenal rates, often more than one meter per year, in many parts of the world. Formerly perennial rivers and streams whose base flow was supplied by groundwater are becoming seasonal or disappearing altogether. Wetlands are drying up. Salt water is intruding inland in many coastal areas, and land is subsiding under cities. Pollution is increasingly threatening those supplies that are available. Water managers have long been accused of suffering from hydroschizophrenia (5, 6), the inappropriate differentiation of the natural interconnection between surface and groundwater and the creation of separate surface and groundwater governance, policy, and bureaucracies. It appears that the double enigma associated with groundwater and its use has further caught the water resources management community off guard.

We have gained from groundwater use, but many fear we are approaching, or are already beyond, its limits. As we dig deeper, however, hopeful options begin to appear. The goal of this article is to provide perspectives on fundamental groundwater issues and the constraints and opportunities we have for improving groundwater use with a review and interpretation of recently published literature and data.

GROUNDWATER AND ITS FUNCTIONS

Groundwater, like all water, exists as part of a hydrologic cycle with no beginning or end. Nonetheless, and concerns over hydroschizophrenia notwithstanding, water as groundwater has a number of particular attributes both in terms of its physical properties as well as in its social uses, which justify separate discussion and study.

Groundwater is generally thought of as that water present below the land surface. More specifically, it is the underground water that fully saturates all fissures and pores below the earth's surface. The definition of groundwater thus does not generally include water stored more temporarily between soil particles near the land surface. The layer of earth, gravel or stone, that can yield groundwater is known as an aquifer.

Groundwater is created by infiltration of precipitation, surface runoff, or water stored in surface bodies, including rivers and lakes, to an aquifer. Groundwater leaves aquifers and reenters the surface system through natural discharge to springs, seepage areas, surface-water courses, or the sea.[1] In general, more upland areas are sources for groundwater recharge (accumulation), and more lowland areas are areas of discharge. In many regions, the natural system of groundwater recharge and discharge has been greatly altered by human activities in recent decades. For example, in large areas of the Indo-Gangetic plains, northern China, and elsewhere, the development of wide-scale surface irrigation has formed a major new source of recharge. Because cities often import and use, but typically do not deplete (evapotranspirate), large amounts of water from surrounding regions, urbanization is also an increasingly important source of local recharge (7, 8). At the same time, the pumping of groundwater for agricultural and urban use has formed new sources of discharge, removing groundwater at a faster rate than local recharge and resulting in declining water tables.

From a physical perspective, groundwater is different from surface water for two main reasons (9). First, it is typified by a large storage volume per unit of inflow (as compared with low ratios of storage to flow as in surface water). This makes groundwater's availability less sensitive to annual and interannual rainfall fluctuations than surface water. The often vast spatial extents of aquifers also make groundwater's distribution highly ubiquitous, underlying most of the earth's surface rather than confined to narrow channels or lakes as is surface water. Second, groundwater typically moves much more slowly than surface water—often at rates measured in meters per year or decade rather than per second.

Groundwater's physical properties contribute to its special function in human systems. Aquifer recharge by filtration through the soil tends to remove and block impurities and creates a source for high-quality drinking water for domestic use. For both domestic and agricultural uses, aquifers serve a natural storage function, providing a substitute for surface reservoirs and a source of supply in the dry season when surface supplies or rainfall are insufficient (10). This stabilization effect has been shown in some circumstances to increase groundwater's value by 50% (11), a number that might increase if rain and surface-water supply variability increases with climate change. The ubiquity of groundwater also tends to make it less capital intensive to access than surface supplies. As a result, development can often be self-financed by even relatively poor users. For these reasons, groundwater has even been called "democratic" (12), and even those unable to afford pumps or whose holdings are of uneconomic size for well development are often supplied by nearby well owners through groundwater markets or other channels (13–17).

However, economies of scale in large surface schemes and the costs of groundwater pumping can make its unit extraction costs higher than for surface water. In addition, unlike

[1]The possible exception is so-called fossil groundwater, groundwater contained in aquifers, which are no longer recharged.

surface irrigation, groundwater users (India being a notable exception) must typically pay at least the marginal cost of extraction in terms of energy. The positive side effect appears to be that groundwater irrigation is generally more productive than its surface counterpart, because cost-sensitive farmers are more judicious in use and because, unlike most surface water, self-supplied groundwater can be delivered precisely when needed (18, 19). For example, it has been estimated that groundwater irrigation in Spain provides five times more value and three times more jobs than surface irrigation (20). Yet, it is not an either-or issue, as it has also been shown that access to groundwater within surface-irrigated areas can substantially increase the productivity of both (13, 17).

IS THERE A GLOBAL PICTURE OF GROUNDWATER AVAILABILITY AND USE?

Consistent data on global, or even regional, aquifer storage, recharge, and use are notoriously difficult to come by. One of the first global assessments was done by a now defunct body of the United Nations (UN) in 1960. Another UN body, the Food and Agricultural Organization (FAO), later noted that the value of developing a global groundwater picture is likely of negligible benefit (21) primarily because groundwater and its problems are largely local.

Despite this admonition, a number of efforts, often with involvement of the UN itself, have been made in recent years to create a global view. Of these, some have focused on the overall water resources system with groundwater as one component. The world water resources estimates of Shiklomanov (22) and the FAO's AQUASTAT database (**http://www.fao.org/nr/water/aquastat/main/index.stm**) are examples. Other efforts have focused more specifically on groundwater itself and have tried to provide both numeric and visual images of the world's major aquifers and recharge patterns. Examples include regional assessments of groundwater resources by Zektse & Everett (23), the World-wide Hydrological Mapping and Assessment Program's (WHYMAP) data, maps of major recharge areas (**http://www.whymap.org/**), a similarly themed map produced by Döll & Flöerke (24) (**Figure 1**, see color insert), and the International Groundwater Resource Assessment Center compilation of regional groundwater data and related mapping resources (25). Finally, a complementary set of works has tried to discern global patterns related to particular aspects of groundwater by building stories from more local evidence. Examples include analyses of agricultural use (26, 27), urban use (23), and degradation (28).

Virtually all authors of global groundwater assessments highlight the problems of data availability and quality and place important caveats on the accuracy of the accompanying numbers. Some probable causes include lack of regionally sufficient monitoring networks, itself a function of monitoring cost; lack of consistent collection standards across and even within countries; insufficient or nonexistent data archiving standards; and the fact that well design must be planned for both extraction and monitoring—a fact often not considered in construction decisions. If data on groundwater resources are of questionable quality, data on its use are even less reliable. AQUASTAT, whose data are assembled at national scales, is one of the few sources which can be used to develop internally consistent figures on global groundwater use. Despite their best efforts at collecting data with the direct support of country experts (29), the quality and timeliness of data varies considerably by country. Given recent rapid changes in groundwater use in some regions, especially Asia, this may result in significant underreporting. For example, recent data for India (30) and China (31) collected from primary surveys, but also supported by recent national statistics, suggest that groundwater-irrigated area, and likely use, may be some 40% higher than currently registered in AQUASTAT.

Although there are clear limitations to any global survey, these assessments do highlight the significance of groundwater in global water availability and use and related trends. Estimates by Shiklomanov (22), for example, show that groundwater makes up about one-third of the world's total freshwater and the vast majority (96%) of all freshwater not bound up in ice. Groundwater is also significant in global water use, accounting for about one-quarter of total water withdrawals (12). However, because groundwater monitoring systems are likely less complete than those for surface waters, the real figure could plausibly be higher. In addition, percentages on the basis of volume probably understate the true role of groundwater in human systems because groundwater use tends to be of higher value than surface water, as mentioned above. In addition, the volumetric figures, dominated by agriculture, understate the key social role groundwater plays for vital domestic water supplies. For example, it has been estimated that 50% of world's current potable water supply is provided by groundwater (32) and that between 1.5 and 2.8 billion people—nearly half the world's population—rely on groundwater as their primary source of drinking water (10). Moreover, more than half the world's megacities (those with populations over 10 million) are groundwater dependent (10), an association which will only grow in importance with increasing urbanization.

Indeed, data gathered for global assessments suggest a major shift is taking place in groundwater use, which, in turn, is bringing new opportunities and problems. Although time series data on groundwater use is, which is not surprising, difficult to obtain, virtually all observers have highlighted the growing trend over the past half century or less as highlighted in **Figure 2** (see color insert) for agriculture. A number of forces are believed to have driven the increase. Urban use has been spurred in particular by the growing global trend in urbanization (8). For both agriculture and urban applications, use has also been spurred as surface supplies have become more polluted and clean groundwater has served as a substitute (10). For agriculture specifically, the main user of groundwater, perhaps the foremost reason has been a technological change in the form of cheap pumping technology (26). Other factors include the initial growth of surface irrigation schemes, especially in South Asia and China, which increase recharge and provide new groundwater sources (26). Later unreliability of these systems may have also prompted additional use as farmers shifted to groundwater as a means to better control supplies.

In fact, the contribution of user self-financing has been a significant and largely unappreciated factor in the global groundwater story. Shah (33) has argued that the value of private investment in groundwater irrigation in India is equivalent to more than three-quarters of the substantial public investment on surface systems. Although much investment in groundwater irrigation in China in the pre-reform period (pre-1979) was collectively financed, the proportion of collective tubewells declined from about 60% in 1995 to 30% in 2004 (34). The change was not due to privatization of existing wells but to rapid growth in additional private investment in well installation and operation. The situation is similar almost everywhere and stands in sharp contrast to surface irrigation financing. This difference has important implications for efforts to regulate groundwater use—in particular for those more familiar with surface irrigation. When individuals self-supply groundwater, they are disconnected from the official water bureaucracy and its standard regulatory and policy levers.

Where the global assessments begin to fall short is when trying to understand the implications of both the current state and recent trends. If analyzed at the global scale, the statistics indicate there is no groundwater problem per se. Despite major groundwater use, demand is still only 600–700 km^3 (35) or ~6% of the estimated 11,500 km^3 (36) annual renewable recharge. Even moving from global to regional scales, there is unlikely any major area where abstraction exceeds recharge, and it has been posited that Yemen may be the only example of such a condition applying to a country as a whole (37).

Table 1 Groundwater use by country[a]

Country	Total groundwater withdrawals (km^3)	Total renewable groundwater resources (km^3)	Percent of withdrawals to total renewable groundwater resources	Percent national share of global withdrawals
India	190	419	45.3	28.9
United States	110	1,300	8.5	16.7
Pakistan	60	55	109.1	9.1
China	53	828	6.4	8.1
Iran	53	49	108.2	8.1
Mexico	25	139	18.0	3.8
Saudi Arabia	21	2.2	954.5	3.2
Italy	14	43	32.6	2.1
Japan	14	27	51.9	2.1
Bangladesh	11	21	52.4	1.7
Brazil	8	1,874	0.4	1.2
Turkey	8	68	11.8	1.2
Uzbekistan	7	9	77.8	1.1
Germany	7	46	15.2	1.1
Egypt	7	2	350.0	1.1
France	6	100	6.0	0.9
Spain	5	30	16.7	0.8
Bulgaria	5	6	83.3	0.8
Argentina	5	128	3.9	0.8
Libya	4	0.5	800.0	0.6
Rest of the world	76	6,135	1.2	11.6
Total	658	11,282	5.8	100.0

[a]Sources: FAO, AQUASTAT (**http://www.fao.org/nr/water/aquastat/main/index.stm**; 40, 41).

However, the use and importance of groundwater are highly uneven spatially. **Table 1** shows the main groundwater-using countries. Just the top five abstractors account for nearly 80% of all use. The top 10 account for nearly 90%.

Even at the national scale, the socioecology of specific groundwater systems cannot be fully understood or appreciated. As generally discernable in **Figure 1**, use within the main groundwater-consuming countries is limited to particular areas. In India where use may be most ubiquitous, extraction is concentrated in the Indo-Gangetic plains and the Deccan Plateau in the south, and there are still areas, especially in the east, where additional development is possible. In the United States, most use is centered on the Ogallala aquifer in the center of the country. In China, use is concentrated mostly in the North China Plain. Only in the use belt across North Africa and the Middle East is groundwater a major supply source across entire nations.

CHALLENGES: GLOBAL, REGIONAL, AND LOCAL

The previous section has argued that there is not a global groundwater problem as such. However, that does not mean that there are not global issues related to groundwater use. In fact, there are both global implications to regional groundwater problems and, probably more importantly, significant opportunities to obtain global insights into the conditions under which various solutions to local groundwater problems may, or may not, work.

Overdraft—Global Implications?

In terms of global implications, probably the single most frequently discussed issue in the literature is the concern that current agricultural output levels are premised on unsustainable groundwater use, bringing into question the availability of future food supplies. As put by the former director of the International Water Management Institute and his coauthors: "The penalty of mismanagement of this valuable resource is now coming due, and it is no exaggeration to say that the results could be catastrophic for [China, India, Pakistan, Mexico and most countries in North Africa/Middle East], and given their importance, for the world as a whole" (38).[2] Ominously, Lester Brown (39) argued that the day when global aquifer depletion will lead to unmanageable global food scarcity may soon be upon us.

The only published guesstimate of global groundwater overdraft places the figure at around 160 billion cubic meters (40), or about twice the annual flow of the Nile. The estimate would probably be revised substantially upward if redone today. Some authors have tried to quantify specific agricultural production impacts of groundwater overdraft, in particular for two of the world's largest consumers of food and groundwater, India and China. For example, the Seckler et al. (38) study, conjectures that perhaps one-quarter of India's food crop is at risk owing to poor groundwater management. Brown & Halweil (41) have suggested that one-half of the North China Plain's wheat production is threatened, and Foster & Chilton (28) have provided calculations resulting in similar figures for the same region. More recently, Brown (39) cited figures that China will lose the ability to feed about 10% of its population when just the aquifer in the Hai river basin is depleted.

There is no question that groundwater use is higher than recharge in many parts of the world, including large parts of India and China. In many cases, the rate of water table decline is alarming. For example, there are many examples in both the alluvial aquifers of the agriculturally critical Indo-Gangetic plains of South Asia and in the hard-rock aquifers of the southern Indian peninsula of water tables falling at rates of one meter or more per year over the last 20 or more years (42). Similar drops are reported for particular parts of northern China (43–45). In a broad survey of users and managers, it was estimated that water tables have dropped by at least 1.5 meters per year for the past 10 years in 10% of the region's villages (19). Similar stories exist across the Middle East (46). The phenomenon is not limited to the developing world. Drawdown is a severe problem in Australia, Spain, and the United States. The drawdown of the large Ogallala aquifer in the central United States—a major grain producing region—is so great that it has furthered calls to let the region depopulate and return to a grazing ground for buffalo (47).

The connection between unsustainable groundwater use by most of the worlds' agricultural powerhouses and global food security seems compelling on the surface. However, without downplaying the important issues that do exist in groundwater management, some have questioned the basis for the assumed connection on a number of grounds, including the lack of documentation of groundwater decline's actual impact on yield or production, a misunderstanding of the meaning of food security, and an underestimate of societies' adaptive capacity both within and outside the agricultural sector (48). Yet others (2, 49) have suggested that claims about the global severity of groundwater problems in general are not as serious as often portrayed and have cited the lack of documented cases where intensive groundwater use has lead to broad economic or social disturbance. As Moench et al. (48) highlight, a clear understanding of the causal linkage, or lack thereof, between groundwater overdraft and global food security is critical for wise policy making; calls for large-scale action based on simplistic models, especially if they

[2]Notably absent from the list are developed country overabstractors, including the United States, Australia, and Spain, the first two of these have a major role in global food markets.

are later disproven, may divert attention away from the fundamental problems.

Clearly there are critical issues associated with drawdown, many of which can have serious local and regional consequences. In terms of the aquifers themselves, drawdown can result in permanent compaction with less ability to hold water in the future, can allow nearly irreversible salt water intrusion (especially but not only in coastal areas), and can increase the risk and severity of contamination (50). Compaction in urban areas often reveals itself in land subsidence. Drawdown can be so severe in urban areas that land subsidence causes damage to urban infrastructure. Perhaps the most notorious recent example is the increase in damage to the city of New Orleans by Hurricane Katrina owing to subsidence from groundwater withdrawal. Beyond the aquifer, drawdown can sever or change the linkages between ground- and surface-water systems, reducing groundwater's ability to provide base flow to streams and wetlands and changing species composition or existence (51, 52). Through the same process, it can also reduce soil moisture levels, negatively impacting the composition and productivity of natural vegetation as well as agriculture. Finally, drawdown increases the costs of drilling, using and maintaining wells, and reduces yield.

From an equity standpoint, there also appears to be a consensus in the literature that drawdown disproportionately harms the poor. As water tables fall, it is those without access to capital for deeper pumping who are cut off from supplies first (13, 33). These are usually the poor. This outcome is exacerbated during droughts when groundwater's buffering value is lost (53). Importantly, these and other impacts on human and natural systems can occur long before there are serious threats to overall groundwater resources. As pointed out by Moench (54), "The Ganges basin contains, in some locations, over 20 thousand feet of saturated sediment. Dewatering of only the top few tens of feet would, however, have tremendous economic and environmental impacts."

The Meaning and Utility of Sustainable Groundwater Use

This brings up the more general debate of what groundwater overdraft actually means. Hydrogeologists traditionally based management plans on the narrow idea of safe yield, a measure of the extraction rate that can be maintained indefinitely without depleting supply (55). As safe yield can ignore uncertainties (e.g., spatially and temporally variable recharge rates) and negative externalities, it has given way more recently to sustainable use concepts, which, at least in theory, call not just for analysis of recharge versus abstraction but for consideration of all undesirable effects related to groundwater use as well as intergenerational equity, i.e., that the needs of the present should be met without compromising future generations (55–57). Nonetheless, safe yield, sustainable yield, overdraft, and overexploitation are all terms commonly used to simply mean abstraction at a rate greater than some normal recharge.

A number of works have highlighted pitfalls in such use of these terms and the potentially flawed policies they may suggest. For example, from a water management perspective overdraft can make storage available for wet season recharge, reducing flood potential and providing water supply in the dry season (10). This indeed seems to be happening in Bangladesh (58). It would also follow from the common usage of these terms that any use of fossil groundwater is overdraft because all abstraction is by definition greater than recharge. Llamas and his coauthors (56, 59, 60) in particular have argued against such interpretations, citing examples such as Libya and Saudi Arabia where there are positive benefits of this obviously unsustainable use with few if any negative consequences.

Importantly, this social line of interpretation has increasingly been used beyond fossil groundwater and applied to unsustainable use in general. For example, Allan (46) has argued that overuse of groundwater has allowed the positive rural economic transitions that have taken place across much of the Middle East and

North Africa over the past 40 years, and similar findings have been highlighted for South Asia and parts of China [e.g., Shah et al. (61)]. More generally, Moench and coworkers (62, 63) have emphasized the value of a socially adaptive, rather than hydrologic, view of groundwater use and overuse. The crux of this viewpoint is that unsustainable groundwater use in the short term can be converted into other forms of capital for the improvement of the human, and possibly environmental, condition in the future. The important policy implications are discussed in more detail below, and analogies can also be found in discussions of hydrologic and socially constructed concepts of drought (64).

Groundwater Quality Degradation

Although this discussion has focused primarily on groundwater quantity, aspects of groundwater quality form other important issue around the world. Groundwater quality issues can be divided into two groups, naturally occurring phenomena such as high arsenic levels (65) and degradation of groundwater resources through human action.

In terms of naturally occurring quality problems, high arsenic (65) and fluoride levels may be the most significant. For example, in South and East Asia, an estimated 60 million people are at risk from high levels of naturally occurring arsenic in groundwater, and some 0.70 million people are thought to be afflicted with symptoms of arsenicosis (66). Arsenic contamination of groundwater is a major drinking water threat and assumes massive proportion in some areas, most famously in Bangladesh. There, it is estimated that as many as 20% of the shallow tubewells, providing domestic supplies to ~30 million people, may be contaminated with arsenic (67). Other affected countries include India, Myanmar, Nepal, Pakistan, Cambodia, China, and Vietnam.

What makes the issue of arsenic contamination particularly challenging is the fact that, although methods for mitigating its impacts are available, they are not always locally affordable. Some studies also show that poor nutritional intake increases susceptibility to arsenic poisoning (68–70), suggesting that overall socioeconomic development may be a longer-term solution. Much arsenic contaminated water in South Asia is also used for irrigation. Even though there have been fears that arsenic could enter the human food chain, the evidence so far has been inconclusive (67, 71). Unlike arsenic, which occurs naturally in alluvial aquifers, fluoride is more of a problem in hard-rock aquifers and is directly linked to overexploitation of groundwater resources. Consumption of excessive fluoride in drinking water can lead to the debilitating disease of fluorosis. It is estimated that 62 million people in India are affected with dental, skeletal, and nonskeletal fluorosis (72).

In terms of human-induced degradation, salinization has been cited as the biggest single threat to aquifer sustainability (10, p. 5). One aspect of salinization, already discussed, is salt water intrusion resulting from aquifer drawdown. A more widespread aspect is the human-induced salt accumulation in the upper soil profile known as secondary salinization. It has been estimated that 20% of the world's irrigated areas are affected by secondary salinization in one way or another (73). India, China, Pakistan, the former Soviet Union, and the United States account for most salinized soils, but the phenomena is also a major national issue in countries with smaller shares of the world's total irrigation, including Argentina, Egypt, and Iran. The consequence of secondary salinization, a problem extremely difficult to remedy, can be vastly reduced productivity and utility of soil and water.

The primary cause of secondary salinization is excess application of irrigation water, raising water tables, and inducing naturally occurring salts to be drawn upward toward the soil surface through capillary force. A second cause, especially in hotter climates, is high evaporation rates, which leave naturally occurring salts in applied water on the soil surface. Salinization through excess water application is not a problem of groundwater per se but rather a function of irrigation management in general, with an impact via groundwater. Salinization through evaporation can be considered a groundwater problem to the extent that the irrigation source is groundwater. Both problems can be solved or exacerbated by changes in irrigation management.

Pakistan provides an interesting case of the creation and management of salinization problems as related to groundwater. The development of large-scale irrigation systems in Pakistan without sufficient drainage led to both water logging and salinization. Government programs were enacted to encourage groundwater use, not as a new source of water but rather as an alleviation measure. Groundwater has since developed into a major irrigation source, and overdraft problems may now be as important as mitigation in groundwater management policy (74).

Although the global extent and distribution of the problem is unclear, groundwater quality degradation via anthropogenic pollution is also a significant threat in many locations. For example, the European Commission has said that groundwater pollution is the most serious problem facing water policy in the European Union (56). Pollution is increasingly a problem in the developing world as well, and there are already extensive problems. The two main forms of anthropogenic pollution are chemical and biological. Chemical pollutants come mostly from industry or agricultural runoff. Biological pollutants are primarily derived from human or animal waste and agricultural runoff. The issues surrounding anthropogenic pollutions differ substantially by form and source. In terms of form, chemical pollutants tend to persist for long periods of time and may therefore contaminate even deep aquifers. Biological pollutants typically persist for only a matter of days or weeks and thus are primarily a threat to shallow water supplies. In terms of source, industrial and domestic pollutants tend to be concentrated (known as point source pollutants) in limited locations with small numbers of actors (e.g., factories and effluent outlets), whereas agricultural pollutants can come from vast numbers of farms spread over wide areas (known as nonpoint source pollutants).

The Problem of Underutilization

Most research related to groundwater management focuses on overuse and abuse, but there are still areas where overabundance is the issue and where additional use is possible. Thus, despite the phenomenal growth in utilization and degradation, there are still areas where the groundwater issue is not so much one of problems but rather opportunities. The possibility of using additional groundwater to alleviate salinization in Pakistan has already been cited. There are also still some significant areas where substantial resource development could take place. Even within parts of the heavily exploited North China Plain, there are areas where additional groundwater use is possible, and it appears that farmers are continuing to develop these additional supplies. For example, Wang et al. (19) note that the share of villages using groundwater for the first time increased 12% from 1997 to 2004. In contrast, eastern India has vast groundwater potential that is not being used. For example, overabundance of groundwater (water logging) is a problem in some parts of India (42), and large areas in the east (e.g., West Bengal) do not yet take full advantage of their groundwater (75). Though not well documented in English, agricultural groundwater use is actually declining in globally important wheat and cotton producing regions of central Asia, partially as a result of post-Soviet institutional and financial change. Although Africa has nowhere near the agricultural groundwater potential of Asia, there may also be examples where further beneficial use is possible (76, 77). Sonou (78) estimated that only 0.2% of recoverable safe yield and 0.02% of groundwater reserves were being used, a situation likely similar today. Underutilization is a potential problem, especially in poor countries, because it reflects a lost opportunity to improve lives. Furthermore, it may mean that alternative sources of water are being utilized with potentially greater environmental costs.

TECHNOLOGICAL AND INSTITUTIONAL OPTIONS

There is a substantial literature documenting a host of possible solutions to both the groundwater quantity and quality problems just discussed.[3] These solutions can generally be divided into two main groups, technological and institutional.

Technological Options

Technology, and the money for implementing new and existing technologies, can provide important options for solving local and regional groundwater problems and increasing water-use efficiency. Here, four general technological approaches are discussed. However, technological solutions can also cause new problems and conflicts if they are not backed by simultaneous institutional change.

Water transfer. The classic solution to water scarcity problems, including those associated with groundwater, has been to increase locally available supply by sourcing from further afield. In terms of groundwater management, imports of new water supplies can be used as a substitute for additional local groundwater use, mitigating problems of drawdown, or as a source of artificial recharge, as discussed in more detail below. Water import is most likely to be physically and economically feasible in urban, rather than agricultural, contexts because the volumes of water needed are relatively small and the returns to use relatively high. The water import model has been used as a purposeful remedy to groundwater problems in numerous locations. For example, the Sardar Sarovar Project in India, which involves transfer of water from the Narmada River from upstream Madhya Pradesh to downstream Gujarat state, has been justified in part on the grounds that it will help recharge the depleted aquifers in north Gujarat (79). China's South-to-North Water Diversion Program could be argued to be the largest such effort as the surface water it moves from the Yangtze basin to the North will go primarily to urban and industrial uses, which now have a high groundwater component (80).

Increased recharge. A second solution frequently discussed is to increase groundwater supplies not by bringing in water from outside but rather by capturing more locally available water through recharge. Groundwater recharge can be accomplished using a variety of techniques and water sources and with varying levels of complexity. Perhaps ironically, operation of inefficient irrigation systems, which allow surface supplies to seep into the groundwater table, is one of the best methods for recharge and plays a major role already in parts of India, Pakistan, and elsewhere. Similarly, inefficient production of wet season crops, such as in a paddy, can help to increase recharge. This process can be helped by building embankments (bunds) around fields to slow runoff and increase infiltration (38). Common calls for more efficient irrigation systems to prevent such losses must therefore be viewed with caution. More purposive efforts to capture water for recharge are also possible as perhaps exemplified by the use of storage tanks (ponds) across much of South Asia (81) or through recharge structures (82). Similar, smaller-scale measures for water harvesting, often related to groundwater recharge, have been advocated for the production of domestic water supplies (83). Locally produced urban wastewater, possibly the only water source whose availability is consistently expanding, also offers large potential for recharge if quality issues can be controlled (28, 84).

Conjunctive use. Groundwater is often used not as the sole source of irrigation but in conjunction with surface supplies. From an

[3] Antropogenic degradation problems are related to the general problem of negative externalities. Potential solutions to negative externalities, related to both source and nonpoint source pollution, have been extensively covered in the non-groundwater literature and so are not explicitly covered here. However, when anthropogenic degradation has unique characteristics related to groundwater, it is discussed, as in the case of wastewater recharge.

individual farmer's perspective, conjunctive use can be effective because the availability of surface irrigation (as well as rainfall) is variable and because groundwater can be used as a buffer to ensure water for crop growth at key times. Conjunctive use can also play a role in improving (irrigation) system or basin water productivity, in particular when there are spatial differences in groundwater quality (85). For example, in Pakistan's Indus valley, groundwater quality in upstream areas tends to be higher (i.e., less saline) than downstream. However, upstream users tend to use surface supplies first, leaving downstream farmers dependent on more saline groundwater. A reversal in pattern, with upstream users pumping high-quality groundwater and downstream users taking surface supplies could improve overall system outcomes (86). Similar possibilities have been noted for many canal irrigation systems in South Asia (13, 87). Although there is scope for well-coordinated conjunctive use, mandating such change is not simple. And as Kemper (88) points out, we should not wait to take action for improved groundwater management until joint surface and groundwater institutions are in place.

Water-saving technologies and changing use patterns. Even though water imports and recharge can directly increase groundwater supplies, water-saving technologies can raise the productivity of those supplies. A vast range of water-savings technologies is already in existence for both agricultural as well as domestic and industrial use. Most of these technologies are not specifically related to groundwater but rather water use in general. Evidence from both the developed and developing world has shown the effectiveness of these technologies in increasing water productivity as measured by the decrease in pumping (or diversions for surface water) necessary to produce a given output (89).

In a similar fashion, productivity can be increased by shifting groundwater use from low- to high-value products or from more- to less groundwater intensive products. Ambast et al. (82) describe how a shift in cropping patterns could contribute to sustainable groundwater management in the Indo-Gangetic plains. Although the key policy question might be how to get farmers to accept their specific suggestions without broader policy or price change, it is clear that farmers will respond on their own to changing groundwater conditions. For example, in parts of eastern India where diesel pumps are used, rising fuel costs have encouraged many farmers to move away from summer paddy to potentially high-return, but higher-risk, vegetables (90). Similarly, Blanke et al. (91) and Wang et al. (19) show that farmers in North China have both increased adoption of water-saving technologies and shifted cropping patterns at least partially in response to changing water resource conditions.

Does water saving save water? The complex nature of water coupled with the human nature to respond to change means that there are important issues to consider in determining whether any of these options will achieve their particular goals. For example, water transfer can be an effective solution to local groundwater problems, but it clearly is not a solution to broader water scarcity problems because it affects not the total quantity of water being used but rather the location from which it is sourced (92). Similarly, whether or not groundwater recharge results in net increases in available water depends on what would have happened to the water otherwise. In many cases, water harvesting captures wet season flood waters that would have had little or no human or environmental benefit and might even have caused flooding. Thus capturing it, and even encouraging its capture by drawing down the water tables in the dry season, may have a positive effect on overall water availability. In other cases though, the captured water might have been otherwise used further downstream. For example, a widespread groundwater recharge movement in the Indian state of Gujarat appears to have been the cause of a sharp decrease in rainfall run-off ratios with significant consequences for an already established drinking water reservoir (81). Which use is better is an open question, but the reality is that trade-offs often exist.

The potential of water-saving technologies to actually save water is also less certain than might appear at first glance. A common assumption in the promotion of these technologies is that reducing water inputs per unit of output is equivalent to reducing water use. This may not be true for two reasons. First, whether reduced inputs translate into actual water savings depends on what would have happened to the saved water. Excess irrigation water applications, as mentioned in the canal-lining example above, often percolate to the groundwater table from where they are recycled through pumping by the same or other farmers and therefore not lost or wasted (93). Second, economic theory tells us that the new technologies may induce farmers to use more of the now more productive resource, thereby increasing overall water use (94). Whether the increased value of the input is offset by decreased need will depend on the particular circumstances. For example, Peterson & Ding (95) showed that new technologies in the central United States did decrease use; however, Ahmad et al. (96) and Kemper (97) showed that overall water use went up with the introduction of water-saving technologies in Pakistan and Yemen.

TRANSBOUNDARY AQUIFERS

The problems of groundwater management can become even more complex when aquifers are shared between two or more independent states. This is perhaps best exemplified in role in the struggle over aquifer sharing between Israel and the Palestinian territories (129, 130). Although there has been substantial work on transboundary waters and water management in general (131), little until recently has focused on groundwater. Furthermore, while literally hundreds of international water agreements are in place, few have seriously recognized or addressed groundwater issues. In fact, it has been only recently that attempts have been made to identify the scale and extent of transboundary aquifers (132, 133) or the status of their management (134). Inaddition, the importance of transboundary aquifers to both water management and the broader issue of international security has been recognized for decades (135, 136). The momentum to raise awareness and examine the special needs of cooperative groundwater management has, however, only recently begun to develop (132, 137–140), with the exception of a few select examples such as the Nubian Sandstone (North Africa) and Guarani (South America) systems, the particular focus of international organizations, in the Middle East where groundwater management is connected to high politics, and in the shared systems of the U.S.-Mexican border.

Institutional Solutions

There is a general feeling that the most promising solutions to water problems shift from increased development (mostly technology based) to management (mostly institution based) as the level of water scarcity increases (e.g., the hard versus soft path delineation of Gleick (98). The same arguments have been made for groundwater [e.g., Kemper (97)]. In addition, it may also be the case that a technological option will only achieve its goals if the right institutional framework is in place. For example, as mentioned above, technologies to increase water productivity may actually increase overall water use if there are no institutional arrangements to limit individual user's abilities to put more of the now more productive resource to use. Three general institutional approaches to groundwater management have emerged from the literature—collective action or community-based approaches, instrumental approaches, and indirect approaches. A fourth approach, adaptation, is discussed below. The special case of transboundary aquifers is addressed in the sidebar Transboundary Aquifers.

Collective and community action approaches. Common-pool resources (CPRs) are resources for which exclusion of prospective users is difficult and whose utilization by one impacts the availability or quality of the resource for others (a property known as subtractability). CPRs contrast with private goods, where exclusion is feasible, and public goods, which do not exhibit subtractability. The management challenge of CPRs derives from the resultant user incentives. The benefits of exploitation tend to accrue to individual users, but the costs of use, in terms of a reduced resource base (known as the scarcity cost in economics) or higher extraction costs, are spread among all. At the same time, the cost of investment in the resource (e.g., groundwater recharge structures) is with the individual investors, but benefits can often be garnered by all users, creating a free-rider problem. The dual result is often an overexploited and degraded system. Groundwater in many ways exemplifies the issues of CPR management.

Although the solutions to CPR problems may have seemed impossible [e.g., Hardin (99)], a substantial body of work over the past 30 or more years has shown that local collective action can successfully meet the challenges, at least under certain circumstances (100). Collective action generally means the creation of use and management rules, and enforcement of those rules, by the users themselves. Collective action appears to have the highest probability of overcoming the challenges of CPR management when the number of users is low, the resource is local (meaning it has limited geographic spread), the users are relatively dependent on the resource for their livelihoods, and they feel they are likely to have repeated interaction with each other into the future.

There is a large literature on the efficacy of local versus central governance of resources in general (101) and trends toward decentralization (101a). In water, the positive stories of local collective action have primarily involved traditional surface irrigation, such as the tank systems of southern India or the famous Subak systems of Bali, where mutual monitoring is feasible. However, there are also examples from groundwater. The traditional management of small-scale qanat (also known as *karez*) systems spread across North Africa and the Middle East provide good examples (102) as do some traditional systems in drier parts of West and East Africa. Grabert & Narasimhan (103) and Schlager (104) have summarized evidence of collective action success in modern groundwater systems in South Asia, Yemen, and Egypt. Although Grabert & Narasimhan (103) note that the success stories are limited, they also stress that, in those examples, collective action was the only option that did work. Other authors have highlighted the potential for local participation in management through the equivalence of water user associations, for example in Mexico (105), Jordan (106), and Spain (107), though the efficacy of those efforts is sometimes unclear or has been questioned [e.g., Wester (108)].

Instrumental approaches: rights, rules, and prices. The key problem in the success of collective or community-based approaches to groundwater management is that the number of users of a particular aquifer can be high and their location geographically spread, thereby increasing the costs of cooperation. In addition, the hidden and dispersed nature of groundwater means that it is often difficult to monitor availability and use, complicating efforts by local users to jointly set and enforce rules. An often proposed solution is for higher level authorities to provide centralized resources to assist in data collection and in information development and monitoring, as well as to set and enforce at least some of the rules to regulate use. These rules can operate alone or form an overarching framework within which collective action by local water users can operate. This model is similar to that of water user associations operating within government run large-scale surface irrigation systems. The general term for these rules is instruments (88, 109).

Two instrumental approaches are most often used and discussed in groundwater management. The first is the assignment of regulations and water-use rights, including rules, permits, entitlements, and licenses, which establish the privileges, restrictions, and obligations of groundwater users. Regulations are typically codified and specify how users in general can and cannot use groundwater. Rights are usually bestowed on individuals or jointly to groups. They can be temporary or permanent and can range from usufruct to fully tradable. Usufruct rights, if established consistent with aquifer conditions, can be applied to limit use to desired levels or control the timing of use so as to reduce interference between users. Tradable rights also allow the possibility of efficiency gains as market processes bid water from low- to high-value uses. The establishment of groundwater-use rights has been more common in developed countries [e.g., the United States (110) and Australia (111)], but they have also been tried in the developing world [e.g., Mexico (105)]. Regulation, at least on paper, is common throughout the world.

The second main instrumental approach is the use of pricing (including taxes). Although water pricing is a major topic in the general water literature, it appears not to have seen widespread use in groundwater. The exception may be in the urban and industrial sectors, where only a minority of groundwater use actually occurs (88). This is likely because the costs of monitoring use and collecting fees is lower in urban than rural settings, where far-flung users typically self-supply groundwater with no connection to formal provision and monitoring systems. It is true that groundwater markets are common in South Asia, China, and elsewhere. However, there is some debate as to whether they are truly water markets or rather markets for water services (e.g., pumping).

The three challenges to the successful implementation of instrumental approaches are in acquiring sufficient information to set overall abstraction levels or prices (if prices are not market set), in establishing acceptable methods for determining how abstraction rights are distributed between users, and in developing mechanisms to enforce rules. Meeting these conditions has not been easy, and in general, the more successful examples (e.g., China) have occurred in urban areas where the number of abstractors (as opposed to users) is low or in developed country agriculture (e.g., Australia) where again the number of users is relatively low and data, technical support, and financial and other resources are high.

Indirect approaches. When groundwater institutions are discussed, we normally think of those institutions directly related to the groundwater sector and that might be connected to the groundwater or water bureaucracy. However, the institutional and policy arrangements that impact groundwater extend far beyond the sector itself (33, 112). The policies from two particular sectors stand out in this regard—energy and agriculture.

India provides the best example of the potential impact of energy policy on groundwater outcomes. From the 1950s through the 1970s, the use of electric tubewells was encouraged in India by both the government and external lenders as a means to agricultural and economic growth. As tubewells spread, metering and fee collection became a major challenge, and a flat tariff system was introduced partially in response. The flat tariff reduced transaction costs in fee collection, but also removed marginal incentives for farmers to use electricity and water efficiency. As importantly, the tariff level became highly politicized. The eventual outcome was that power for agricultural groundwater use has become essentially free in India's major groundwater-using regions, encouraging overuse and simultaneously draining the funds of state electricity boards (26). A World Bank study (113) concluded that power sector subsidy in India amounts to Rs 270 million per year (US$6.0 billion), two and half times the annual state expenditure on canal irrigation (perhaps three-quarters of the total can be connected to irrigation).

The government of India has embarked on reforms, one of the main components of which is agricultural power supply metering, to address the linked energy-groundwater problems. Although few states have agreed to reforms, an initial assessment of one which has, West Bengal, suggests that they are having an impact on both the volume of groundwater extracted and the efficiency of its use (114). Rather than power metering, another Indian state, Gujarat, has instead decoupled agricultural electricity supply from rural domestic and commercial electricity supply (112). They then ration the number of hours of electricity supplied to the agricultural sector and let households and other sectors have unrestricted access. Again, there has been a direct impact on the volume of groundwater extracted (112). Similarly, there is evidence that in diesel-dependent eastern India, the rise in diesel prices in the early 2000s led to decline in irrigated area (16, 115). Although the extent to which India's groundwater overdraft problem is energy related is not known, it is clear that energy costs, and therefore energy policies, do play a significant role in groundwater-use decisions.

A second important policy arena with impacts on groundwater is agriculture. The choices farmers make about the type and quantity of crops they produce is often heavily influenced by national agricultural policies. In some cases, the connections between these policies, farmer decisions, and water use are relatively easy to trace—for example the Conservation Reserve and Payment-in-Kind Programs in the United States provided incentives for farmers to reduce cropping, thereby reducing groundwater use in the Ogallala aquifer (116). In other cases, the connections, and how they change groundwater use, are less obvious. For example, in the 1950s and 1960s, the international community expressed genuine concern about the world's ability to feed its future populations. One response was the launch of the Green Revolution, an effort to increase food supply by investing in research to increase crop yield through the development of new, hybrid seeds. In terms of yield increase, the Green Revolution was clearly a success. However, the new hybrid varieties typically required new farming systems. These systems often required greater control and use of water, and in many cases, this was facilitated by groundwater. In fact, it has even been argued that the Green Revolution was first of all a tubewell revolution (117). Thus, in some senses, current groundwater outcomes in many countries are a function of agricultural policy decisions a half century ago. Additional examples of the connection between agricultural policy and water use are given in (117a) for the specific cases of Haryana in India and the European Union.

The difficulties in implementing community-based and instrumental approaches to groundwater management have already been highlighted. Indirect approaches are not necessarily any easier. India has struggled over reforms of its energy sector for decades, and the difficulties in changing agricultural policy are well documented worldwide. At a minimum, recognizing the potential positive and negative groundwater impacts of energy, agricultural, and other policies before they are enacted help may help to reduce unintended consequences, consequences that can be very difficult to reverse once new interests become politically entrenched.

THE REAL CHALLENGE—INSTITUTING CHANGE

Nitin Desai, former Under-Secretary-General at the UN Department of Economic and Social Affairs, stated that as early as 1960 that a group of eminent hydrogeologists hired by the UN had identified the upcoming problems of, and workable solutions to, intensive groundwater use but that these solutions had not been applied (118, p. v). His statements perhaps inadvertently drive to the heart of the groundwater challenge. It is one thing to describe potential technological and institutional solutions to groundwater problems. It is quite another to actually implement them.

The previous section has highlighted the difficulties in reforming institutions and policies to positively impact groundwater. Nonetheless, the literature is replete with solid technical studies of groundwater problems that offer clever possible solutions but whose success requires appropriate institutional frameworks. For whatever deficiencies we still have in basic data and scientific understanding, it is an understanding of how to determine and implement those appropriate frameworks in which we appear to be most deficient.

Scattered throughout the groundwater management literature are examples of successes and more commonly, but as importantly, failures and the factors surrounding why they happened. Although the exact definition of success varies by perspective and location, some general conclusions about the groundwater conditions with the highest likelihood for workable solutions can be culled from the literature.

Low Number of Users or Small Aquifers

Consistent with CPR theory in general, it appears that aquifers with a low number of users are easier to govern, either through collective action or state-sponsored intervention, than aquifers with high numbers of users. Two immediate implications emerge. The first is that aquifers used for agriculture in the developed world are generally easier to govern than those in the developing world, at least for the time being. The simple reason is farm structure. For example, Shah et al. (18) point out that the successful Santa Clara Valley Water Conservation District in California, United States (103), probably contained fewer than one thousand farmers, whereas a similarly sized aquifers in Asia would have had 100 times as many. Even in sparsely populated Australia, the transaction costs of governing small users has been recognized, and those with less than two hectares of land have been excluded from a licensing system. The same rule in South Asia (35) or China would exclude nearly all users.

The second implication is that urban groundwater problems will tend to be easier to confront than rural, at least as far as extraction is concerned, because the number of entities abstracting groundwater (as opposed to the number of final consumers) tends to be smaller. In some cases, the municipal government may be the only direct abstractor. The examples of Jakarta and Bangkok provide the exceptions to prove the rule (10). In Jakarta, many lower-income households are excluded from the municipal water system. As a result, they have resorted to self-supplied groundwater to meet their drinking and other needs. As abstraction problems have caused land subsidence, flooding, and salt water intrusion, the government has found it difficult to implement solutions because of the large number of people to be managed. In Bangkok, domestic use was successfully regulated, but there was no mechanism to control use by large numbers of private industrial users.

Local Groundwater Problems in the Context of Regional Water Availability

Not surprisingly, groundwater problems appear to be more soluble when they exist in an environment of overall water abundance, or at least where alternative water sources are available to be tapped or imported as a substitute for groundwater use. Again, this is most likely to occur for urban uses, where the total volumes needed are relatively low. The city of Beijing tapping water from a nearby reservoir, initially constructed for irrigation, provides one such example. Agricultural examples also exist, for example in California (103), as do those for environmental uses as in the Azrak Oasis of Central Jordan (119). As cautioned earlier though, such solutions to groundwater problems are unlikely to be solutions to overall water scarcity but rather a shift in the location of water sourcing.

Significant Resources to Finance Change

The California and Jordan examples just cited were made possible in part because of the availability of significant financial resources sourced at least in some measure beyond the groundwater users. In the case of California, both water users and government agencies provided funds. In Jordan, funds were derived both from the national government and international actors. Other examples of funding as a factor in reform success include the American southwest and Australia. The availability of funds to compensate those who will lose their rights to groundwater or to construct infrastructure to provide groundwater substitutes can be a key to reform success. Whether such financing is economically efficient is another question. However, it does appear to be a factor in overcoming the political economy problems, which often confront efforts to reform groundwater policy.

Attitudes Toward and General Functioning of Governance

Cohen & Bakker (120) analyzed the groundwater governance systems on two small islands, one on each side of the Canadian/U.S. border. Those on the Canadian side generally supported groundwater regulation, and many thought additional regulation was needed. Users on the U.S. side were identified as having an antigovernment mind-set. One nongovernmental organization even felt that not associating itself with government organizations helped it to achieve its goals of groundwater conservation and protection—goals presumably also held by the government. Even within the United States, differential attitudes toward governance between western U.S. states have been shown to be reflected in groundwater policy strategies and outcomes. For example, having credible enforcement mechanisms—a form of trust—even if they are not actually applied can assist in achieving desired groundwater results (121). That differences in attitudes about governance can differ between and within countries with similar physical settings and historic backgrounds has clear implications for efforts to transport groundwater policies and management ideas across or even between regions (e.g., India and China).

DISCUSSION AND CONCLUSION: IS A BROADER VIEW OF RESOURCE SYSTEMS THE REAL SOLUTION?

The preceding section highlighted the conditions under which formal solutions to groundwater management problems are most likely to succeed. What about the regions where the conditions for improved groundwater governance are not met? Unfortunately, these regions account for the vast majority of the world's groundwater use, resulting in groundwater governance regimes that have been described as a "colossal anarchy" (122). Fortunately, a set of recent scholarship has provided insights into why the prognosis for this anarchy may not be as dire as first appears and what can be done to ensure that worst case scenarios do not develop. The two keys are time and adaptive opportunities.

The importance of time in the development of groundwater opportunities, problems, and possible solutions has been graphically illustrated in similar ways by three major articles on groundwater management (61, 88, 123). Although each of the papers differs in their prognoses, the fundamental story behind their depictions is that demand or technology prompts an initial foray into groundwater use. The attractiveness of groundwater plus the open-access nature of the resource result in use expanding unabated. At some point, use becomes unsustainable, leading to social conflict or a decline in the groundwater economy. Though none puts an explicit scale on their time lines, a period of one to three generations is sometimes discussed.

The temporal dimension of a pathology may be especially import in understanding groundwater outcomes because of the physical nature of groundwater. The size of storage and the slow rate of flow mean that it may take a generation or more of overabstraction before it is clear that a problem is present. Two results follow which make governance difficult. The first is that there is no impetus for institutional development because the true scarcity—and thus a value in management–may not be perceived until problems are well underway. The second is that the lag between problem onset and perception may mean that individuals and governments have continued to invest in the resource even after scarcity problems have begun, resulting in those with vested interests who may struggle to continue use, even if it eventually means the end of the resource.

While time may appear to be the villain, it may in fact be the saviour. In 1900, half or more of the populations of the United States, western Europe, and Australia were agricultural. Today, the percentage is in the low single digits. Similar demographic transitions are also now occurring in much of the developing world. China is now experiencing the most rapid rural outmigration in history, with the equivalent of the entire U.S. population moving to urban areas in just the past 20 years. Although the transition in South Asia is slower, it is still rapid by any historical standards. The result will be that the proportion of people closely reliant on agricultural groundwater, where use is greatest and governance most difficult, will drop from near 50% (26) today to perhaps less than 10% over the next half century. This change, as discussed earlier related to common property management regimes, may increase the chances for better management by reducing the number of resource users and increasing each user's stake in positive resource outcomes. It would, in fact, bring the share of the agricultural workforce to levels not dissimilar to California, the southwestern United States, Australia, and Spain, which have had some success in managing groundwater.

Directly related to time as a driver of demographic change is its role in economic change. China has been growing at 10% a year for nearly 30 years now. India is again behind but has been growing at a face pace for the past 10 years. This growth will help to provide the resources that have been used to achieve groundwater management solutions elsewhere. Perhaps as importantly and in contradiction to some conventional wisdom, growth in water use appears to delink itself from overall economic growth once a threshold is reached (124–126). This has probably already begun in China and offers additional hope for lowering pressure on groundwater in South Asia.

In fact, there is evidence that groundwater use, rather than sowing the seeds for its own destruction, actually sows the seeds for its own sustainability. Llamas & Martinez-Santos (127) have argued that one catalyst for the economic transition in Spain, which reduced the share of the labor force in agriculture from 50% to 6% over just 50 years, was groundwater. This transition freed labor for more productive work in the urban sector and at the same time left those still in farming in a better position to use new technologies and grow crop with higher water productivity.

The Spanish example highlights another role of time—the possibility it gives for adaption (127a). In a direct sense, it has been shown that groundwater institutions can adapt to change. Groundwater institutions for well management and ownership rapidly changed in China for example (19), and their growth and evolution has been shown in Texas (128). Even when formal institutions do not adapt fast enough, groundwater users have consistently been shown to adapt to changing resource conditions by reducing pumping, adopting water-saving technologies, and changing cropping patterns, as highlighted above.

However, it is adaptation in the broader sense of the term that is probably more important. The key question is whether people are able to take the benefits of, sometimes unsustainable, groundwater use and turn them into other forms of capital, which will make them less dependent on, or independent from, the resource in the future. The possibilities and the pitfalls of adaptation are highlighted in Shah's (13) well-known book on groundwater in one of the most intensively used aquifers in the world, the coastal aquifer of Saurashtra in Gujarat, India. There, high rates of pumping led to locally unprecedented levels of prosperity, and the area acquired the term "Green Creeper." However, overuse soon caused drawdown and seawater intrusion. "The foresightful among the well-off farmers saw the writing on the wall, and used their resources to make a careful and planned transition from farming to off-farm occupation[s] in nearby towns. The less foresightful and/or the less resourceful stayed behind and took the full brunt of the fall of the socio-ecology" (13).

The possibilities of a successful adaptive outcome is highlighted in an aptly titled paper by Moench (63), "When the Wells Run Dry, but Livelihoods Continue" in which he describes how such a transition can take place. Although not precluding other technological and institutional options, his emphasis is on facilitating the conversion of groundwater into other forms of capital and providing means to make the new capital productive. In other words, a system in which livelihoods adapt to mitigate the impact of groundwater pressure. Thus, the core goal of groundwater management may sometimes be to allow society to adjust to groundwater conditions rather than attempting to manage the resource base itself.

SUMMARY POINTS

1. Aquifers possess multiple properties that make the groundwater they contain highly valuable for a variety of human uses, including the provision of drinking water, irrigation supplies, and a range of environmental services.
2. These properties, coupled with recent expansion of low-cost pumping technologies, have led to an often unrecognized boom in groundwater exploitation in the last few decades. Groundwater now accounts for approximately half of all drinking water supplies and a major portion of all irrigation supplies.
3. The growth in groundwater utilization has brought widespread benefits for global economic development, including urbanization and rural poverty reduction.
4. However, governance mechanisms to manage groundwater use have not kept pace with the changing situation. As a result, while there are still options for expanded use in some regions, quality decline and aquifer depletion are now major issues in many parts of the world.
5. Although a variety of technological and institutional options have been identified and applied to improve groundwater outcomes, the open-access nature of the resource and the political economy of water management have limited their success, particularly as related to the largest consuming sector, agriculture.
6. Nonetheless, there is evidence that even where traditional groundwater interventions have failed, policies based on a broad view of resource systems and human adaption could provide new solutions.

FUTURE ISSUES

1. Nearly all observers highlight deficiencies in data and information on groundwater availability and use as well as the physical and social impact of that use. These deficiencies exist from local to regional to global scales and thus form a key knowledge gap and area for additional research.
2. However, whatever deficiencies we still have in basic data and scientific understanding, it is the fundamental understanding of how to determine and implement location appropriate frameworks for groundwater management in which we appear to be most deficient.

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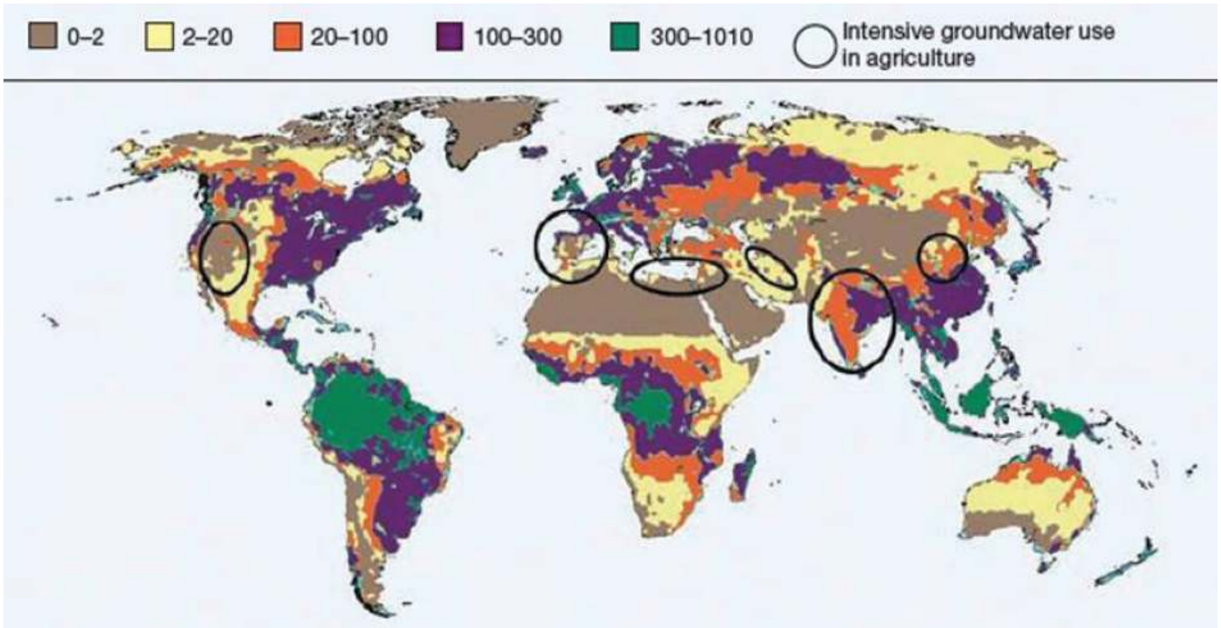

Figure 1

Long-term average groundwater recharge (in mm/year) and areas of intensive groundwater use (26).

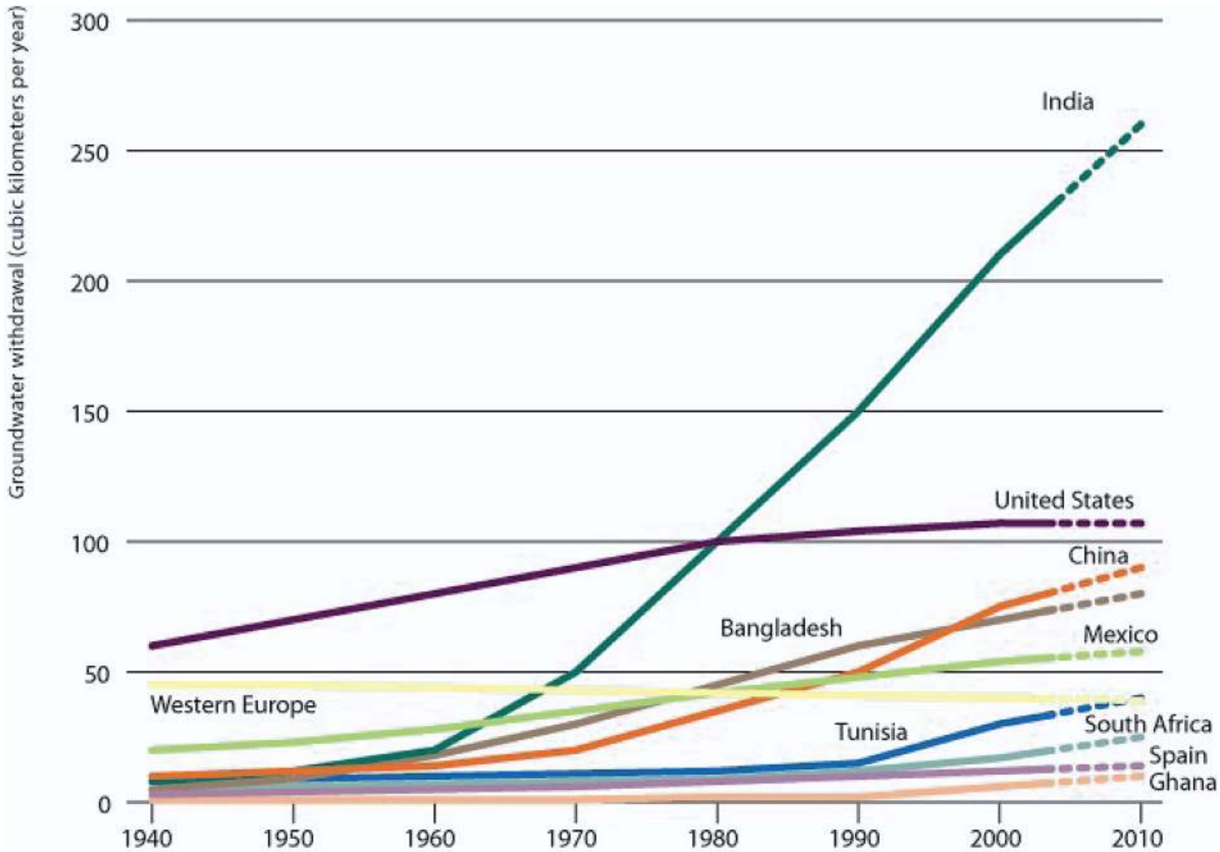

Figure 2

Trends in agricultural groundwater use (26).