Groundwater boom and bust?

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10 Groundwater: a global assessment of scale and significance

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Overview

Intensive groundwater use in agriculture has become a dominant, yet underperceived aspect of contemporary water use. While the use of groundwater has its roots in many ancient civilizations, it has grown exponentially in scale and intensity over recent decades. Global abstraction of groundwater grew from a base level of 100–150 cubic kilometers in 1950 to 950–1,000 cubic kilometers in 2000. The bulk of this growth is concentrated in agriculture, particularly in Asia *[established but incomplete]*.

Groundwater has contributed significantly to growth in global irrigated areas since the 1970s. The irrigated areas supplied wholly or partly by groundwater are officially reported at 69 million hectares (ha), but independent studies suggest a higher figure, closer to 100 million ha, up from approximately 30 million ha during the 1950s *[established but incomplete]*.

While millions of farmers and pastoralists in Africa and Asia have significantly improved their livelihoods and household food security, aquifer depletion and groundwater pollution are also a direct result of this intensive use of groundwater, implying that existing trends cannot be sustained unless accompanied by far more intensive regimes of resource management than are currently deployed. The groundwater boom has been driven by supply-push factors, such as government subsidies and easy availability of inexpensive pumps and drilling technologies. Demand-pull factors have also contributed, arising from groundwater's capacity to provide flexible, on-demand irrigation to support vibrant, wealth-creating agriculture in all climate zones and from the growing need to provide food for urban populations. By far the most powerful pull has been in South Asia and North China, where the land-augmenting impact of groundwater has proved irresistible.

Globally, agricultural groundwater use of around 900 cubic kilometers a year supports annual output valued at $210–$230 billion, yielding a gross productivity of about $0.23–$0.26 per cubic meter of water abstracted [speculative]. However, much of this use is concentrated in Bangladesh, China, India, Iran, Pakistan, and the United States, which account for well over 80% of global groundwater use. The dynamic impacts of intensive groundwater use are best understood by recognizing four types of groundwater-in-agriculture systems:

The groundwater boom has been driven by supply-push factors, such as government subsidies and easy availability of inexpensive pumps and drilling technologies. Demand-pull factors have also contributed

- *Arid agricultural systems*, such as in the Middle East and North Africa, where groundwater is increasingly needed and demanded in higher value nonfarm uses.
- *Industrial agricultural systems*, such as Australia, Europe, and the western United States, where groundwater supports wealth-creating agriculture and attracts more scientific and material resources to manage its negative externalities.
- *Smallholder farming systems*, such as South Asia and the North China plains, where groundwater irrigation creates relatively little wealth but is the mainstay of 1–1.2 billion poor female and male farmers.
- *Groundwater-supported extensive pastoralism*, such as much of Sub-Saharan Africa and Latin America, where groundwater abstractions are less than in other systems but are crucial for water supply schemes and for an extensive pastoral economy that supports a large share of its female and male herders.

In smallholder agrarian systems and groundwater-supported extensive pastoralism the socioeconomic impacts of groundwater irrigation are unassailable.

Overwhelming evidence from Asia suggests that groundwater irrigation promotes greater interpersonal, intergender, interclass, and spatial equity than do large irrigation projects. Evidence from Africa, Asia, and Latin America also suggests that groundwater is important in settings where poor farmers find opportunities to improve their livelihoods through small-scale farming based on shallow groundwater circulation. Once these inherently vulnerable shallow groundwater circulations are threatened, so too are the millions of rural livelihoods tied to them.

This intensive—but essentially unplanned—groundwater use faces several challenges. Pumping costs are rising, and irrigation-supporting subsidies are compromising the viability of rural energy providers. India is a prime example. Moreover, the impacts of groundwater depletion on water quality, stream flows, wetlands, and downgradient users in certain pockets are rapidly nullifying the widely dispersed beneficial impacts on livelihoods and food security at the society level. In arid regions, where fossil groundwater is a primary source of water for all uses, intensive groundwater irrigation may threaten future water security. In addition, with anticipated shifts in precipitation patterns induced by climate change, groundwater's value as a strategic reserve is set to increase worldwide. The challenges bring the central issue of the sustainability of groundwater use systems into sharp focus.

The long-term sustainability of groundwater systems is not easily determined. And a debate has emerged among hydrogeologists over the widely used notion of sustainable yield of aquifers. To manage groundwater resources properly and to identify effective resource management strategies urgently needed among the poorest agrarian societies, an improved understanding of aquifer behavior has to be combined with an appreciation of the socioeconomic drivers of intensive groundwater use.

In the face of such growing concerns, groundwater use in agriculture is showing no sign of ebbing. It will continue to grow in many parts of the developing world. Participatory approaches to sustainable groundwater management will need to combine supply-side measures—such as artificial recharge, aquifer recovery, interbasin transfer of water, and the like—with demand-side measures—such as groundwater pricing, legal and regulatory control, water rights and withdrawal permits, and promotion of water-saving crops and technologies. But not all these measures are immediately suited to developing countries if approached from a formal water management perspective. Supply-side measures have proved easier to implement than demand-side measures, even in technologically advanced countries. In the absence of supply augmentation the only way to adequately ease the strain on aquifer systems may be to reduce irrigated areas, improve farming practices, and shift to water-saving crops—but this may be difficult to implement in socioeconomic and political terms in developing countries.

> **The opportunities and challenges presented by the growth in intensive groundwater use in agriculture are often under-represented in global discussions of the challenges of water scarcity**

The long-term strategy to ease pressure on groundwater resources may be to increase opportunities for off-farm livelihoods and ease population pressure on agriculture. In the medium term key priorities in Latin America and Sub-Saharan Africa are to develop groundwater for improving the livelihoods of poor male and female farmers but in a regulated and planned manner. In Asia's groundwater hotspots key priorities are to develop effective indirect and direct means to regulate aggregate groundwater withdrawals; step up investments in groundwater management, including widescale managed aquifer recharge and scientific conjunctive management; and conduct judicious and well planned interbasin transfers of water. In all parts of the developing world a key common priority is to improve the data base, upgrade the understanding of groundwater supply and demand conditions, and create effective programs for public education in the sustainable use of groundwater resources.

Global trends in groundwater irrigation

Rapid growth in groundwater irrigation has dominated expansion in global agricultural water use during recent decades. Global abstraction of groundwater grew from 100–150 cubic kilometers in 1950 to 950–1,000 cubic kilometers in 2000, largely concentrated in agriculture, particularly in Asia. The opportunities and challenges presented by the growth in intensive groundwater use in agriculture are often underrepresented in global discussions on the challenges of water scarcity. The goal of this chapter is to assess this revolutionary phenomenon in terms of its socioeconomic, hydrogeological, and environmental fallouts. The chapter also explores where the global groundwater irrigation economy is headed in the coming years and the options available for socioecological sustainability.

Historical context

With the introduction of the tubewell and mechanical pump technology in the early decades of the 20th century and their growing popularity after 1950, groundwater use soared to previously unthinkable levels after 1950 in many parts of the world. In Spain groundwater use increased from 2 cubic kilometers per year to 6 over 1960–2000 (Martinez-Cortina and Hernandez-Mora 2003). In the Indian subcontinent groundwater use soared from around 10–20 cubic kilometers per year before 1950 to 240–260 by 2000 (Shah and others 2003). In the United States groundwater's share in irrigation water increased from 23% in 1950 to 42% in 2000 (Winter and others 1998). Chinese history records occasional cases of farmers lifting water from shallow wells by barrels to irrigate vegetables. But North China had very little irrigation until 1950, and its tubewell irrigation revolution took off only after 1970. In sum, then, the silent revolution in groundwater irrigation is essentially a story of the past 50 years (Llamas and Custodio 2003).

> Groundwater has increasingly come to dominate agriculture in many parts of the irrigating world

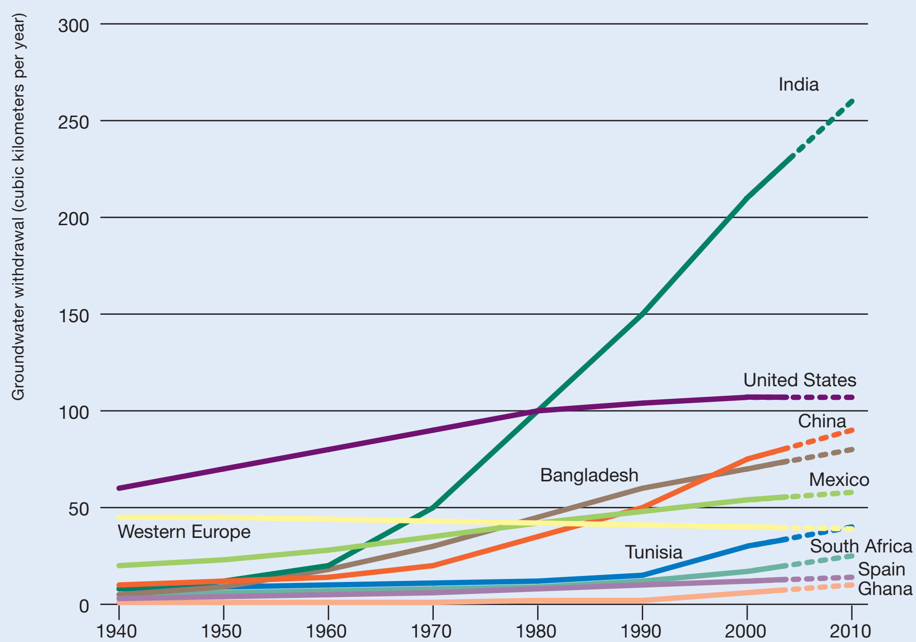
Despite this exponential growth in groundwater use in agriculture, the world is still using only a fraction of earth's known groundwater reserves. At less than 1,000 cubic kilometers per year global groundwater use is a quarter of total global water withdrawals but just 1.5% of the world's annually renewable freshwater supplies, 8.2% of annually renewable groundwater, and 0.0001% of global groundwater reserves (estimated to be 7–23 million cubic kilometers) (Howard 2004). Yet its contribution to human welfare is huge. Groundwater has historically supplied domestic water requirements in numerous human settlements, urban and rural, around the world. According to one estimate, more than half the world's population relies on groundwater for its drinking water supply (Coughanowr 1994).

Irrigated agriculture, however, remains the major user of groundwater, which is often of high quality, suitable for direct human consumption. Understandably, the competition for such high-quality water is now intense, especially for shallow groundwater circulation that can be readily accessed by individual farmers and rural communities for livelihoods and food security. The explosion in groundwater irrigation in some key regions of the world presents a complex resource management challenge. Though global in purview, this chapter emphasizes developing countries where groundwater use in agriculture is high and increasing and where the associated challenges of sustainable resource management are critical for rural livelihoods.

Temporal patterns

Data on groundwater use are scarce. Data on the impact of agricultural groundwater use on food security, rural livelihoods, and ecological systems are even more so. But there is little doubt that groundwater has increasingly come to dominate agriculture in many parts of the irrigating world. Moreover, groundwater irrigation around the world over the past century has emerged and proceeded in waves. The first wave was in Italy, Mexico, Spain, and the United States, where large-scale groundwater use began in the early parts of the 1900s and seems to have peaked—or at least to have stopped growing. The second wave began in South Asia, parts of the North China plains, and parts of the Middle East and North Africa during the 1970s and is still continuing (figure 10.1).

In other regions of the world, however, groundwater use in agriculture has been slight but shows signs of rapid growth in the near future. In northeast Sri Lanka groundwater irrigation took off only during the early 1990s (Kikuchi and others 2003) and is still growing. Groundwater use in agriculture in much of Sub-Saharan Africa is still very slight and concentrated on commercial farms. But groundwater is increasingly important in supporting extensive pastoralism. A third wave of growth in groundwater use is thus likely figure **10.1** Development in groundwater withdrawal in selected countries



Source: Shah 2005.

table **10.1** Groundwater irrigation in a global context

Continent	Area under groundwater irrigation (thousands of hectares)	Groundwater-irrigated area: Share of total irrigated area (percent)	Groundwater-irrigated area: Share of cultivated area (percent)
Africa	2,472	19.8	1.0
Latin America & Caribbean	3,383	18.6	2.1
Asia	51,863	28.9	9.0

Source: FAO 2005a.

in many regions of Africa and in some South and Southeast Asian countries such as Sri Lanka and Viet Nam (Molle, Shah, and Barker 2003), although a good deal of pumping of water there takes place from surface water.

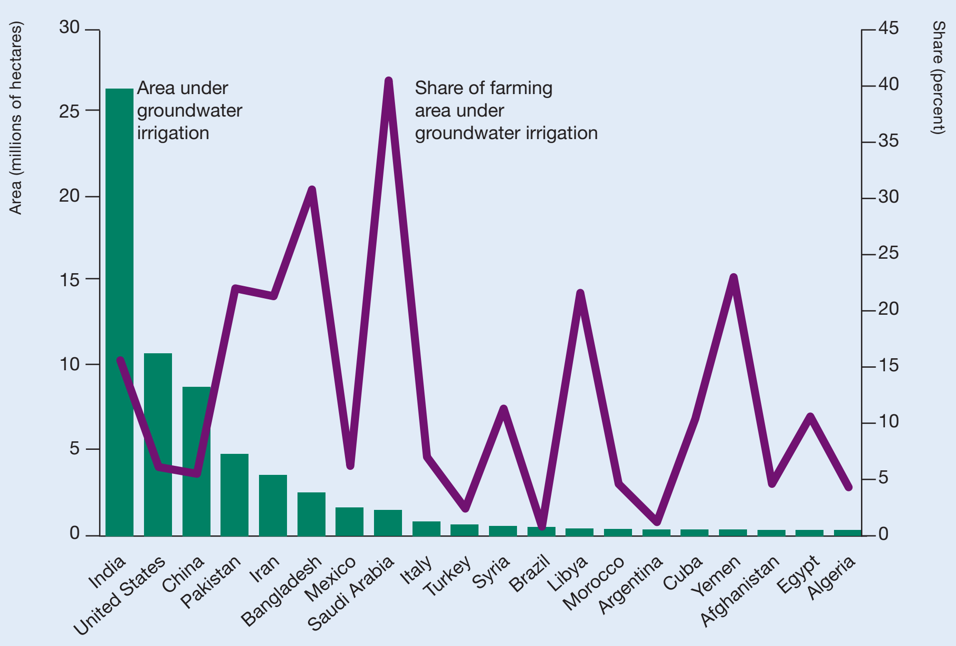
Scale of groundwater use in agriculture

A complete global picture of groundwater use in agriculture is not available. The Food and Agriculture Organization's AQUASTAT database provides national data on irrigated areas supplied by groundwater and surface water as reported by national agencies from developing countries and countries in transition (table 10.1). But since many of these countries do not regularly report data on groundwater-irrigated areas, this coverage is not comprehensive and does not necessarily present an up-to-date picture.

Taking just the developing countries and countries in transition from central planning, some 58 million ha—just 4% of total farm land—are under groundwater irrigation. But 25% of global irrigation depends upon groundwater, and 75% of groundwater-irrigated areas of the world are in Asia.

Information from other sources, however, suggests that total area under groundwater irrigation in 2005 may be 25%–40% higher than reported by the Food and Agriculture Organization.[1] For many countries accurate official estimates are simply not available.[2] For many other countries available estimates are out of date by a decade or longer. For India, the largest groundwater irrigator in the world, official estimates of area under groundwater irrigation are based on a 1993–94 census of groundwater structures. But recent large-scale nationwide surveys suggest that groundwater irrigation in India has experienced explosive growth during the past decade (see, for example, India NSSO 1999, 2003; Shah, Singh, and Mukherji 2006).[3] The 2001 Census of Minor Irrigation by the government of India suggests that gross area irrigated by groundwater wells in India is 53 million ha (India Ministry of Water Resources 2005). Similar trends are noted by researchers in the North China

figure **10.2** **Top 20 groundwater irrigating countries**



Source: FAO 2005a.

plains (Wang and others 2006a). If these estimates are accurate, groundwater-irrigated areas in Asia may well be in excess of 70 million ha, and global groundwater irrigation may well approach 100 million ha *[established but incomplete]*.

Global pockets of intensive groundwater use in agriculture

Since groundwater use in agriculture is concentrated in a few countries—and often in pockets within them—disaggregated analysis is necessary. Based on AQUASTAT data, of the 20 countries with the largest areas registered under groundwater irrigation and accounting for 99% of recorded groundwater irrigated areas, six of them—Bangladesh, China, India, Iran, Pakistan, and the United States—account for 83% of the world's groundwater-irrigated areas (figure 10.2, table 10.2). Because this chapter's assessment is about groundwater use in agriculture, these global pockets of intensive groundwater irrigation are of special interest.

table **10.2** **Top 20 groundwater-irrigating countries**

Country	Cultivated land per agricultural worker (hectares)	Area under groundwater irrigation (thousands of hectares)	Share of global groundwater-irrigated area (percent)	Groundwater-irrigated area		Groundwater-irrigated area (percent of total area)
				Share of irrigated area (percent)	Share of total cultivated area (percent)	
India	0.6	26,538	38.6	53.0	15.6	8.1
United States	63.8	10,835	15.8	45.5	6.1	1.1
China	0.3	8,863	12.3	16.0	5.5	0.9
Pakistan	0.8	4,871	7.1	30.8	22.0	6.1
Iran	2.6	3,639	5.3	50.1	21.3	2.2
Bangladesh	0.2	2,592	3.8	69.1	30.8	18.0
Mexico	3.2	1,689	2.5	27.0	6.2	0.9
Saudi Arabia	6.0	1,538	2.2	95.6	40.5	0.7
Italy	11.2	865	1.3	27.2	7.0	2.9
Turkey	1.9	672	1.0	16.0	2.4	0.9
Syria	3.3	610	0.9	60.2	11.3	3.3
Brazil	5.9	545	0.8	19.0	0.8	0.1
Libya	22.9	464	0.7	98.7	21.6	0.3
Morocco	2.4	430	0.6	29.0	4.6	1.0
Argentina	24.1	403	0.6	27.7	1.2	0.1
Cuba	5.2	393	0.6	45.1	10.4	3.5
Yemen	0.6	383	0.6	79.6	23.0	0.7
Afghanistan	1.2	367	0.5	11.5	4.6	0.6
Egypt	0.4	361	0.5	10.6	10.6	0.4
Algeria	3.0	352	0.5	61.8	4.3	0.1

Two other categories of area are also of interest. First are regions where the dominant source of water for all uses is fossil groundwater, such as the Middle East and North Africa. Some countries in these regions—with significant areas under groundwater irrigation—are in the list of top 20. Another region of interest is Sub-Saharan Africa, where groundwater use is small relative to the resource potential. Careful and planned development of the resource can make groundwater an important part of a poverty-reduction toolkit for this region. There is already movement in this direction. The general impression among researchers is that groundwater use is insignificant in Sub-Saharan Africa, and its role in supporting livelihoods equally so. Recent explorations, however, suggest that quantities of groundwater annually withdrawn may be smaller than in South Asia or the United States, but groundwater already plays a significant role in supporting livelihoods in Sub-Saharan Africa by sustaining extensive pastoralism (Giordano 2006), irrigated agriculture, and water supply.

Careful and planned development of groundwater can make it an important part of a poverty reduction toolkit for Sub-Saharan Africa

Driving forces

Ready access to groundwater drilling technology and borehole mechanization led to the widespread uptake of groundwater in the second half of the 20th century. This trend was anticipated as early as the mid-1950s (UN 1960). What has not been so easily explicable is the intense regional differentiation, that is, rapid growth in Asia and the notable absence of growth in much of Africa and Latin America. This section attempts to review the principal drivers behind such regional disparities.

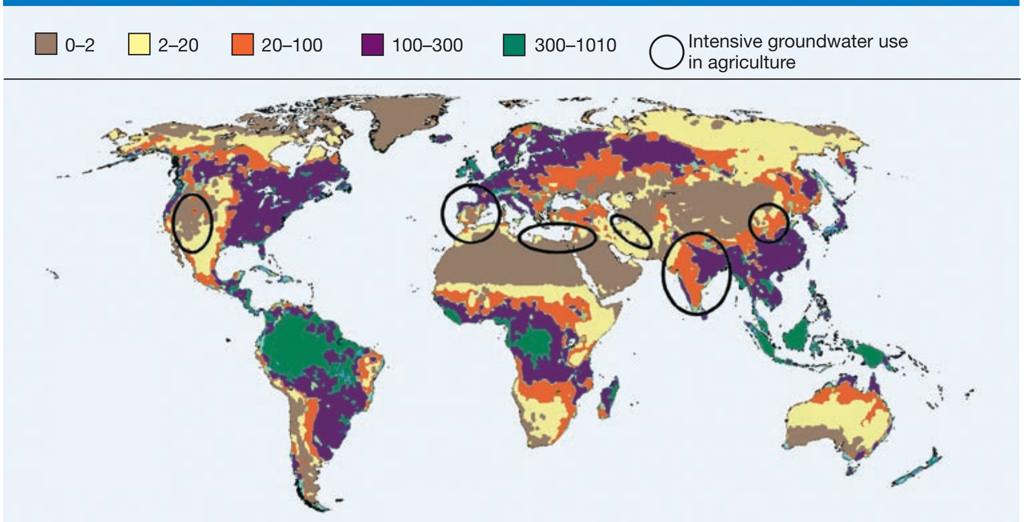
Water scarcity

The global groundwater boom in recent decades has occurred in regions with limited rainfall and hence recharge. The countries where pressures to intensify agricultural production have been acute have witnessed intensive groundwater use in agriculture.

A new global map developed by researchers at the Technical University of Dresden shows the average annual groundwater recharge in different parts of the world (map 10.1). None of the 20 countries listed in table 10.2 falls in areas with high average annual recharge of 300–1,000 millimeters (mm). Groundwater use in agriculture is absent or minimal in regions with high recharge, and it is intensive where the recharge is too small to sustain intensive groundwater use. Notable exceptions are Bangladesh, eastern India, and Nepal's Terai region—humid areas with abundant surface water resources where large pockets of intensive groundwater irrigation have emerged and played a significant role in improving food and livelihood security for the rural poor.

On-demand groundwater services

Another argument explaining the groundwater revolution emphasizes groundwater's many favorable characteristics. First, it is ubiquitous, available in lesser or greater degree, almost everywhere. Second, unlike large surface irrigation structures that may necessitate government initiative or cooperative effort on a large scale, groundwater irrigation can be developed quickly by individual farmers or small groups. Third, while operating costs of groundwater may be higher, the capital costs of groundwater structures are much lower per map **10.1** Long-term average groundwater recharge (millimeters per year)



Source: Döll and Flörke 2005.

hectare of irrigation than those of surface structures. Fourth, groundwater irrigation also demonstrates greater drought-resilience; groundwater aquifers keep yielding during a dry year even when all surface water bodies dry up. Fifth, and most important, groundwater provides irrigation on demand, offering a high-class captive irrigation source that provides farmers freedom to apply water when their crops need it the most. Sixth, due to its reliability in time and space, transmission and storage losses (for example, leakage and evaporation) from groundwater irrigation are lower than with surface irrigation. As a result, farmers tend to economize on its use, optimize other inputs (such as seeds, fertilizers, and pesticides), and diversify crops to more higher valued crops, thereby yielding significantly higher water productivity (in terms of kilograms per cubic meter of water and of dollars per cubic meter of water) than with surface water sources (Shah 1993; Burke and Moench 2000; Deb Roy and Shah 2003; Hernandez-Mora, Martinez-Cortina, and Fornes 2003).

These unique advantages of groundwater are important in explaining why millions of farmers throughout the world have taken to groundwater irrigation. However, these are not enough to stimulate intensive groundwater use in the vast high-recharge regions that are well endowed with groundwater (see map 10.1). This suggests that other drivers of the groundwater revolution are at play.

Access to cheap drilling, pumps, and electricity

The extensive use of groundwater in agriculture has been limited by the labor intensity and high cost of lifting groundwater with human labor and animal traction. Advances in and easy access to pumping and drilling technologies and spread of rural electrification have meant that groundwater development has offered opportunities to tap this beneficial resource for improving agriculture and livelihoods. In many Asian countries, especially China and India, growth in groundwater structures gave rise to a large and competitive industry to manufacture pumps, engines, motors, and drilling rigs, resulting in progressive decline in real prices of this equipment. Governments in many countries, such as India, Jordan, Mexico, Syria, and for some years Pakistan, stimulated groundwater irrigation by subsidizing energy for pumping (photo 10.1). Others, such as Bangladesh and later Sri Lanka, supported groundwater irrigation first by subsidizing equipment costs and more recently by opening their markets to cheap Chinese pumps. One reason that smallholder irrigation experienced explosive growth in South Asia but has grown very slowly in Sub-Saharan Africa is the absence of rural electrification combined with the prohibitive costs of importing pump and irrigation equipment in Africa.

> The unique advantages of groundwater are important in explaining why millions of farmers throughout the world have taken to groundwater irrigation

Pressures of feeding an urbanizing population

As towns and cities grow, their demand for food grows too. Urban consumers need quantity and demand quality. Irrigation has been the principal strategy to maintain national food security in Malaysia and Morocco. Increasing year-round global consumption of fruit and vegetables has prompted the mobilization of groundwater near urban centers such as Lusaka and several cities of China to furnish both urban markets and also feed into export markets.

As the global demand for animal protein increases, groundwater is increasingly called on to provide more water for livestock on rangeland without surface water or for irrigating fodder under zero-grazing systems. Many arid and semiarid rangelands depend entirely on access to groundwater to sustain stocking ratios. But groundwater structures both encourage stocking ratios higher than the range (fodder) capacity and concentrate livestock around boreholes. The self-limiting balance of rangelands can be severely disrupted by the


Photo by David Molden

Photo 10.1 Supplemental irrigation in Syria introduction of mechanized boreholes. Gomes (2005) cites examples from Somalia and northern Kenya where boreholes have encouraged overstocking and resulted in disputes between borehole owners and local communities. The oversized groundwater economy of northern Gujarat and many other arid and semiarid regions in India centers around zero-grazed dairy production (Singh and others 2004). Groundwater is intensively used here to produce fodder and other cash crops, with manure being returned to the land to improve soil quality. This white revolution has been pulled by the establishment of large and highly successful dairy cooperatives that offer reliable and stable markets for milk produced by smallholders in the region. However, the apparent success is limited by aquifer reserves, which in some parts of the state are showing signs of overdevelopment.

Many arid and semiarid regions of the world offer excellent farming conditions suitable for intensive cultivation. The only missing input was water

Agricultural demand in arid and semiarid regions

Many arid and semiarid regions of the world offer excellent farming conditions suitable for intensive cultivation: good alluvial soils, flat lands, and climate with sunshine suitable for supporting two or more crops per year. The North China plains, the Indus Basin, California, and central Mexico are examples. The only input that these areas have lacked for supporting vibrant agriculture was water. Agriculture in many of these regions performed below its potential under rainfed conditions. For millennia farmers in the North China plains harvested three crops every two years using rain and soil moisture (Dong 1991), and the vast and fertile Indus Basin supported extensive pastoralism but was sparsely populated and hardly cultivated. Many of these regions are also located above abundant aquifers, but lifting water manually or with animal labor has restricted the use of these aquifers. The rise of groundwater irrigation with tubewells and mechanical pumps transformed many of these into highly productive agricultural areas. The key driver of the groundwater revolution here was the demand pull for water control through irrigation—the only missing input that kept agriculture in these areas from performing at full potential.

Pressures of rural populations struggling to survive

A widely prevalent view is that intensive groundwater irrigation emerges only in arid and semiarid areas otherwise suitable for intensive agriculture. However, Bangladesh, Nepal's Terai region, and eastern India—all of them humid and endowed with ample surface water resources—challenge this view. And these observations cannot be brushed aside as outliers because they account for a large share of the global groundwater economy, no matter which criterion is used: groundwater-irrigated area, groundwater abstraction, or number of people affected.

The groundwater revolution in these pockets is also driven by demand pull but of a different kind. The massive demand pull for groundwater irrigation in these areas has been powered by tremendous increases in population pressure on agriculture since 1960. Intensive agriculture based on groundwater irrigation has emerged in all densely populated pockets, such as Punjab in India and Pakistan, eastern India, Bangladesh, and Tamil Nadu and Andhra Pradesh in India. By contrast, sparsely populated regions—such as the central Indian highlands and Sindh and Baluchistan in Pakistan—make far less intensive use of groundwater irrigation. Bangladesh, eastern India, and Nepal's Terai region are the only areas where high average annual recharge of 300–1,000 mm is matched by intensive use. But there are also vast regions, especially in peninsular India, with intensive groundwater irrigation but very small average annual recharge. South Asia is thus a region where groundwater development has had little to do with the availability of recharge; the revolution has been driven primarily by the capacity of borewell irrigation to make multiple cropping of land possible and thereby serve as a land-augmenting technology (Mukherji and Shah 2005).

In South Asia groundwater development has had little to do with the availability of recharge; the revolution has been driven primarily by the capacity of borewell irrigation to make multiple cropping of land possible and thereby serve as a land-augmenting technology

Socioeconomic impacts

Global use of about 900 cubic kilometers of groundwater a year in agriculture indicates annual final output of about $210–$230 billion, with gross productivity of $0.23–$0.26 per cubic meter abstracted. In the global economy groundwater-supported output would be a tiny part, and if groundwater irrigation around the world suddenly halted, the global economy would hardly notice. But the socioeconomic impacts of intensive groundwater use in agriculture are important to understand because of the critical links to the livelihoods and food security of some 1.2–1.5 billion rural households in some of the poorest regions of Africa and Asia (photo 10.2). To understand these impacts, it is important to explore the dynamic of groundwater use in agriculture in different regions of the world.

Global typology of groundwater irrigation and impacts

The drivers for intensive groundwater use in agriculture—as well as its broader socioeconomic impacts—differ throughout the world. A meaningful approach to understanding the global economics of groundwater irrigation needs to distinguish between four types of agricultural groundwater use situations: arid agricultural systems, industrial agricultural systems, smallholder farming systems, and groundwater-supported extensive pastoralism (table 10.3). These situations differ from each other in overall climatic, hydrological, and


Photo by David Molden

Photo 10.2 Use of groundwater in Asia is critical to livelihoods, especially for the poor demographic parameters; land-use patterns; organization of agriculture; and relative importance of irrigated and rainfed farming. They also differ in the drivers of expansion in groundwater irrigation and the nature and level of societies' involvement in groundwater-based irrigated agriculture.

Arid agricultural systems have low population pressure on land and a tiny fraction of their geographic area under cultivation. Farming depends on irrigation, mostly from fossil—or limitedly renewable—groundwater, which is the only source of irrigation. But growing competition for fossil groundwater from higher value uses, especially urban water supply, will crowd out its agricultural use. The virtual water thinking pioneered by Allan and others (Allan 2003; Delgado and others 2003; Warner 2003) best applies to arid agricultural systems.

In industrial agricultural systems—as in Australia, Italy, Spain, and the United States—groundwater sustains some highly productive industrial agriculture. Irrigated agriculture is a small proportion of total agriculture, and groundwater is, in turn, a relatively small proportion of irrigated agriculture. Few people depend on groundwater-based agriculture, but more people depend on agribusiness. Industrial agricultural systems have pockets of severe groundwater depletion and pollution due to groundwater irrigation. But agribusiness is a high-value use and creates massive wealth. California's $90 billion agricultural economy depends heavily on groundwater use, as does Spain's export economy of grapes, citrus, olives, fruit, and vegetables. Industrial agricultural systems bring vast financial and scientific resources to ameliorate problems of groundwater abuse, offering a scientific and institutional knowledge base for sustainable groundwater management.

In South Asia and the North China plains intensive groundwater irrigation reflects the population pressure on agriculture (Bruinsma 2003). Smallholder farming systems cultivate a larger proportion of their geographic area, irrigate more of their cultivated area,

table **10.3** **Four types of groundwater economies**

	Arid agricultural systems	Industrial agricultural systems	Smallholder farming systems	Groundwater-supported extensive pastoralism
Countries	Algeria, Egypt, Iran, Iraq, Libya, Morocco, Tunisia, Turkey	Australia, Brazil, Cuba, Italy, Mexico, South Africa, Spain, United States	Afghanistan, Bangladesh, North China, India, Nepal, Pakistan	Botswana, Burkina Faso, Chad, Ethiopia, Ghana, Kenya, Malawi, Mali, Namibia, Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, Zambia
Groundwater-irrigated areas	Less than 6 million hectares	6–70 million hectares	71–500 million hectares	More than 500 million hectares of grazing area supported by boreholes for stock watering
Climate	Arid	Semiarid	Semiarid to humid, monsoon climate	Arid to semiarid areas
Aggregate national water resources	Very small	Good to very good	Good to moderate	Mixed rainfed livestock and cropping systems

(continues on next page)

table **10.3** **Four types of groundwater economies** (continued)

	Arid agricultural systems	Industrial agricultural systems	Smallholder farming systems	Groundwater-supported extensive pastoralism
Population pressure on agriculture	Low to medium	Low to very low	High to very high	Population density is low but pressure on grazing areas is high
Share of total land area under cultivation	1%–5%	10%–50%	40%–60%	5%–8%
Share of cultivated areas under irrigation	30%–90%	2%–15%	40%–70%	Less than 5%
Share of irrigated area under groundwater irrigation	40%–90%	5%–20%	10%–60%	Less than 1%
Share of total geographic area under groundwater	0.12%–4.0%	0.001%–1.5%	1.6%–25.0%	Less than 0.001%, but groundwater-supported grazing areas are about 17% of total area
Organization of agriculture	Small to medium-size farms under market-based agriculture	Medium-size to large-scale farms under industrial, export-oriented farming	Very small landholdings, subsistence-oriented, mixed peasant farming systems	Small-scale pastoralists, often seasonally connected with small-scale agriculturalists
Driver of groundwater irrigation	Lack of alternative irrigation or livelihood	Highly profitable market-based farming	Need to absorb surplus labor in farming through land-augmenting technologies	Stock watering
Significance of groundwater irrigation to national economy	Low (less than 2%–3% of GDP)	Low (less than 0.5% of GDP)	Moderate (5%–20% of GDP)	Moderate (5%–20% of GDP)
Significance of groundwater irrigation economy to welfare of national population	Low to moderate	Low to very low	Very high (40%–50% of rural population and 40%–80% of food production involve groundwater irrigation)	Low in terms of numbers of pastoralists involved, sometimes moderate in terms of national food supply
Significance of groundwater irrigation for poverty reduction	Moderate	Very low	Very high	Groundwater central to pastoral livelihood systems, but limited scope for using more groundwater for poverty reduction
Gross value of output supported by groundwater irrigation	\$6–\$8 billion	\$100–\$120 billion	\$100–\$110 billion	\$2–\$3 billion

Source: Data on cultivated areas under irrigation are from FAO 2005b; data on irrigated areas under groundwater irrigation are from FAO 2005a. Other data are preliminary estimates by the authors.

and use groundwater over more areas for intensive agriculture than do arid agricultural systems and industrial agricultural systems. While in arid agricultural systems and industrial agricultural systems groundwater is used on 0.1%–4% of geographic area, in pockets of smallholder farming systems—such as the Indo-Gangetic Basin—up to a quarter of the total geographic area can be under groundwater irrigation.

In terms of groundwater quantity and number of people involved, the smallholder farming systems in Bangladesh, China, India, Iran, Nepal, and Pakistan have experienced the largest growth by far in groundwater use over the past 35–40 years. Of the global annual groundwater diversion of 950–1,000 cubic kilometers half or more is likely accounted for by these countries. By stabilizing rainfed peasant farming and facilitating multiple cropping, groundwater use in smallholder farming systems affects a larger proportion of population, of cultivated area, and of gross domestic product than in arid agricultural systems and industrial agricultural systems. The challenge of sustainably managing groundwater resources is most serious here, but it is also the most complex.

In terms of groundwater quantity and number of people involved, the smallholder farming systems in Bangladesh, China, India, Iran, Nepal, and Pakistan have experienced the largest growth by far in groundwater use over the past 35–40 years

Groundwater-supported extensive pastoralism is concentrated predominantly in Africa. In Sub-Saharan Africa groundwater resources are modest, but a very small proportion of what is available is currently developed and plays a critical role in supporting extensive livestock (Sonou 1994; Giordano 2006). Groundwater abstraction per hectare is small and is mainly used for stock-watering. The absolute number of poor people who depend on groundwater-supported extensive pastoralism may be smaller than the number who depend on groundwater-irrigated agriculture in Asia. But pastoralists account for a substantial proportion of Africa's population. In Sub-Saharan Africa, where the challenge of improving rural livelihoods persists, groundwater-supported extensive pastoralism is critical in creating a global picture of groundwater's contribution to human welfare (box 10.1).

Groundwater-intensive, market-driven irrigated agriculture

The specific value of groundwater to agriculture is apparent only where irrigation schemes depend entirely on groundwater sources. Burke and Moench (2000) have summarized accounts of the boost that groundwater gives to agricultural production and the attendant environmental stability that groundwater confers. Specific studies are also captured in the Food and Agriculture Organization's 2004 inventory of valuation studies (FAO 2004). Key characteristics are:

- *Available on site*. Groundwater that is available on site needs little conveyance infrastructure thus leading to decentralized management.
- *Storage and reliability*. Groundwater storage provides an important interannual buffer at a fraction of the cost of conventional surface water storage.
- *Flexibility.* Pumped groundwater is a perfect delivery system for farmers. The on-demand, just-in-time characteristics of the system overcome the uncertainty and risk often associated with surface water deliveries. Few surface irrigation schemes can be as perfect and low risk, even if they have good downstream control.
- *Conjunctive use*. In surface water irrigation schemes conjunctive use of surface water and groundwater can make categorical attribution difficult, although farmers in

surface water commands who also have access to groundwater are clearly able to boost overall productivity (see below on conjunctive management of groundwater and surface water).

Groundwater irrigation and rural poverty

In smallholder farming systems the advantages of groundwater irrigation translate into reduced poverty, better food security, and improved livelihoods. In India more than 70% of irrigated agricultural production is attributed to groundwater irrigation (Deb Roy and Shah 2003; India NSSO 2005). Many have dubbed the green revolution in India a "tubewell revolution" (Repetto 1985). And Bangladesh's *boro* rice revolution, which transformed the country from a rice importer to an exporter, is also attributed to its shallow tubewell revolution (Palmer-Jones 1999). For a long time North China farmers raised only three rainfed crops of maize and wheat in a two-year cycle. But the expansion of groundwater irrigation made two crops every year of maize and wheat the standard practice in most of the North China plains (photo 10.3; Wang and others 2006a).


Photo by Tushaar Shah

Photo 10.3 Groundwater provides flexible and reliable supply in China

In these regions productivity-enhancing impacts of groundwater irrigation worked through several pathways:

- *Increased cropping intensity.* Groundwater irrigation made double—or even triple—cropping of farm land possible, making it a land-augmenting intervention in these land-poor regions.
- *Stabilized rainfed* kharif (*monsoon season*) *crop*. Because of the high variability in amount and timing of rainfall from the southwest monsoon, the *kharif* crop always suffered from high production risks. Groundwater irrigation reduced these risks.

box 10.1 | Groundwater and poverty alleviation in Africa

Use of agricultural groundwater is lower in Sub-Saharan Africa than in Asia, but it is critical for livestock production in large parts of the Sahel and East Africa (Burke 1996), and it supports small-scale but highly valuable irrigation and stabilizes the drinking water supply (BGS 2004; Calow and others 1997; Carter and Howsam 1994). While the volumes used may be small, a majority of poor rural households, which make up most agricultural producers in Sub-Saharan Africa, depend on groundwater in some way—for direct crop production, livestock watering, or domestic supplies.

In many parts of Sub-Saharan Africa groundwater is not yet used; in others it has been sustainably used over long periods of time; and in still others depletion is already a problem. For groundwater to contribute more to poverty alleviation, it is important to consider the links between technical feasibility and economic and political realities. Where it makes economic sense, farmers are quick to take to groundwater use. For instance, despite the supposed high costs of irrigation development in Africa, farmers in southeastern Ghana have transitioned from hand-dug wells to diesel pumps to electrification over a relatively short period. Similarly, diesel pump technology introduced in Nigeria after the oil boom spread quickly elsewhere in the region. The point of future development policy as related to groundwater in Sub-Saharan Africa should thus be to understand both where additional development is possible and where and why it is not (Giordano 2006).

- *Reliability.* Supplemental groundwater irrigation's reliability promoted agricultural diversification. High-value crops like fruits and vegetables require more frequent, on-demand irrigation than well owners are able to provide.
- *Geographically widespread benefits of supplemental irrigation.* In Sub-Saharan Africa groundwater has played—and will continue to play—a much less direct role in agriculture, affecting perhaps less than 1% of cultivated area (Giordano 2006). But almost 20% of the irrigated area in Africa is served by groundwater (30% in North Africa and 10% in Sub-Saharan Africa). This is 0.35% of the continent's cultivated area (FAO 2005a).[4] Groundwater sustains Africa's pastoral economy and small pockets of value-added peri-urban agriculture.

Given the trends in groundwater use and the current set of drivers, overall groundwater use in agriculture is not expected to decline in the foreseeable future—but there are signs that the patterns and styles of use are changing

Gender and equity issues in groundwater use in agriculture and pastoralism

Especially in Asia the evidence is overwhelming that the groundwater boom has demonstrated greater interpersonal, interclass, and interregional equity in access to irrigation—and thereby to benefits of intensive agriculture—than large canal irrigation projects that have created pockets of prosperity in command areas (Shah 1993; Deb Roy and Shah 2003; Bhattarai and Narayanamoorthy 2004; Moench 2003).

Some researchers have found that women have little to say or do in managing canal irrigation (van Koppen 1998; van Koppen, Parthasarathy, and Safiliou 2002; Shah and others 2000). However, numerous studies in Africa, Asia, and Latin America show that when women explore ways to improve their livelihood through smallholder agriculture or livestock, groundwater and small pumps are commonly involved. Conversely, poor women and men are hardest hit by groundwater depletion or quality deterioration.

Prospects for sustainable groundwater management

Given the trends in groundwater use and the current set of drivers, overall groundwater use in agriculture is not expected to decline in the foreseeable future. But there are signs that the patterns and styles of use are changing. These changes present both threats and opportunities.

Making the transition from development to management

In many parts of the world where the sustainability of groundwater irrigation is in serious question governments and management agencies have operated in resource development mode far too long. Before tubewell technology became popular, government policies aimed to encourage groundwater use in agriculture through subsidies for capital and operating costs and at times through government installation and operation of tubewells, as in South Asia (Shah 2000), China (Wang, Zhang, and Cai 2004), and Central Asia. Many governments—such as in Sri Lanka and in several African countries—are still in that mode.

However, where intensive groundwater irrigation is already well established, concern is growing among governments, nongovernmental organizations, media, and the general public about the consequences of groundwater depletion and degradation. Country responses are similar: a groundwater organization is set up merely to monitor and study groundwater changes. Once threats are visible, there is a clamor to pass laws to regulate groundwater development by establishing a system of permits to install tubewells and withdraw groundwater. Unfortunately, such measures in isolation are not adequate to curb further groundwater development.

> Where intensive groundwater irrigation is already well established, concern is growing about the consequences of groundwater depletion and degradation

Managing groundwater supply

A natural response to groundwater scarcity is to search for new water sources. However, since development of groundwater is usually secondary to development of surface water, new options for expansion of water supply sources become increasingly limited and costly.

Managed aquifer recharge and rainwater harvesting. Rainwater harvesting and artificial (or enhanced) recharge are popular attempts to capture and store underground rainwater and discharge, termed "excess runoff" or "rejected recharge" (photo 10.4) Rainwater harvesting increases groundwater recharge at the expense of immediate runoff. It may increase stream flow later in the season, when the artificially recharged groundwater discharges to streams. Thus, artificial recharge can be used to mitigate floods and to enhance late-season stream flows.

In India rainwater harvesting is a bylaw in urban construction regulations in such cities as Chennai, Delhi, and Rajkot, and artificial recharge is promoted and financially supported by the government. At the local level rainwater harvesting has gained the character of a mass movement, especially in such regions as western India, where groundwater exhaustion is a real impediment for agricultural activities (Shah 2000; Shah and Desai 2002; Sakthivadivel and Nagar 2003; Agarwal and Narain 1999). This has not been without controversy. The ability of rainwater harvesting to generate new water services in upstream areas will always need to be set against the reduction of downstream flows (Rao and others 2003).

Photo by Tushaar Shah

Photo 10.4 Recharging aquifers through rainwater harvesting in Dudhara, India

Augmenting groundwater with wastewater. In many parts of the developing world cities depend increasingly on groundwater, often to the detriment of farmers in suburban and rural areas. In turn, steadily increasing amounts of wastewater generated by cities, often discharged into streams, have given rise to a new water resource that farmers have opted to use as an alternative (Scott, Faruqui, and Raschid-Sally 2004; Bhamoriya 2002; Buechler, Devi, and Raschid-Sally 2002). This resource is dependable in quantity but poor in quality because untreated wastewater from cities in the developing world can contain harmful pathogenic micro-organisms, excessive nutrients, and toxic chemicals. In most places wastewater use is not subject to any control or surveillance (see chapter 11 on marginal-quality water), posing health risks to farmers using the water and people eating crops grown with wastewater—and causing environmental impacts such as groundwater contamination and disruption of ecosystems in downstream areas. An alternative is to deliberately infiltrate wastewater into groundwater, thereby augmenting the groundwater resource and obtaining partial treatment through filtering processes within soil and aquifer materials (Foster and others 2003).

Conjunctive management of surface water and groundwater. Conjunctive water use refers to the coordinated use of surface water and groundwater to meet demand. Conjunctive management refers to deliberate and planned efforts to comanage surface water and groundwater resources to optimize benefits from new water development projects in terms of productivity, equity, and environmental sustainability. As opportunities for developing newer sources of irrigation are rapidly exhausted, sustainable aquifer management depends greatly on better planning and management of conjunctive use of surface water and groundwater.

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A key strategy in conjunctive management of surface water and groundwater is the planned drawing down of the water table in the pre-monsoon dry months to enhance recharge from monsoon rainwater as well as from irrigation return flows. The conjunctive water management scheme in China's People's Victory Canal used water from wells and canals for irrigation, recharged groundwater with canal water, and used groundwater for nonagricultural purposes. It successfully reduced waterlogging and salinization, alleviated conflicts over low stream flows, reduced sedimentation problems in canals and drainage ditches, assured timely delivery of irrigation water, and increased agricultural production (Cai 1988). This win-win arrangement has, however, broken down in recent years (Pearce 2005).

In the developing world conjunctive use is ubiquitous by default. For example, Dhawan (1988) showed that the mushrooming number of wells in India changed the profile of water use in Mula command in Maharashtra and argued that the indirect benefits of canal irrigation through groundwater recharge are even greater than the direct benefits of flow irrigation. Similarly, Scott and Restrepo (2001, p. 176) concluded that in the Lerma-Chapala Basin in central Mexico, "the sustainability of groundwater trends is inextricably linked to the management of surface water, and is highly sensitive to the area and type of crops irrigated, as well as surface water management practices." The pumping of water from drainage canals for rice planting is routinely observed in South Asian commands, and the use of shallow groundwater pumping from waterlogged soil along leaky conveyance canals is also commonplace. Recent reviews of progress in the Indus Basin note the impact of conjunctive use on farmer incomes but point out that there has been no attempt at conjunctive management (Van Halsema 2002; Wahaj 2001; Strosser 1997).

Scavenging of surplus groundwater on the margins of surface-supplied schemes points to conjunctive use, but not management (FAO 2001). The Loukos pressurized scheme in Morocco effectively provides groundwater at its margin to private irrigators beyond the scheme perimeter, a supply that is sustained through free draining soils. Realizing the multiple uses of irrigation water, this scavenging of leakage water through wells may also provide farming households with better drinking water than other local sources, as in Pakistan and Sri Lanka (Boelee and van der Hoek 2002; Ensink and others 2002; Meijer and others 2006; Shortt and others 2003).

> Key to effective conjunctive management of surface water and groundwater resources is improved main system management, which sometimes requires changes in infrastructure but is more a question of capacity building, efficient organization, and better information and communication

Conjunctive management is rare in developing countries. But in high-income countries conjunctive management is highly developed—enough to even out spatial and temporal variations in regional water availability (Blomquist, Heikkila, and Schlager 2001). In the Phoenix, Arizona, irrigation commands surface water has been banked for future use by agriculture (Lluria and Fisk 1995). Surface irrigation practices have a direct impact on groundwater recharge. Key to effective conjunctive management of surface water and groundwater resources is improved main system management, which sometimes requires changes in infrastructure but is more a question of capacity building, efficient organization, and better information and communication.

In regions with primary salinity—such as the Indus Basin in Pakistan and northwest India, the Nile Basin, the Yellow River Basin in North China—the objective of conjunctive management is to maintain both water and salt balances. System managers require more control and precision in canal water deliveries to different parts of the command to maintain an optimal ratio of fresh and saline water for irrigation (Murray-Rust and Vander Velde 1992). Depending on the aquifer characteristics and water quality parameters, it may make sense to divide the command areas into surface water irrigation zones and groundwater irrigation zones. Recharge structures within a surface system are often useful for rehabilitation and modernization. Another benefit of integrated groundwater and surface water use in irrigation commands has been reduced waterlogging problems in areas where groundwater is pumped to control groundwater level rise and to augment irrigation potential, as in Pakistan (Van Steenbergen and Oliemans 2002).

The benefits of conjunctive management have been realized for municipal water supply to protect stressed aquifers (Todd and Priestadt 1997). But aquifer storage and recovery as tools for managing supply have so far been restricted to municipal uses, where water quality standards have to be maintained and the injection and cycling of treated water does not suffer any loss of quality (Pyne 1995). Given the high costs of injection and recovery, this application is unlikely to benefit low-value agriculture that is indifferent to quality.

The prospects for conjunctive management in agriculture alone look bleak. Where conjunctive use is applied with good results, the legacy of the surface water design and overall management of surface water commands rarely permits precision application of surface water, let alone planned recharge of aquifers whose storage has been opened up.

Only the proximity of higher value uses is likely to prompt more active management of groundwater recharge and discharge.

Interbasin water transfers. In countries with vastly contrasting climate conditions another management strategy for dealing with water deficiency is large interbasin water transfer schemes that attempt to level out and democratize overall access to water resources by transferring water from water-rich regions to water-deficient ones. One example is the San Joaquin Valley of California (box 10.2).

China is similarly planning transbasin diversions from the Yangtze in the water-surplus south to the water-short Yellow River Basin in the north (Liu and Zheng 2002; Keller, Sakthivadivel, and Seckler 2000; Liu and You 1994). India has talked about a garland canal to link Himalayan rivers with Cauveri and other South Indian rivers, but these have remained at the idea level. Generally, supply-augmenting interventions (such as rainwater harvesting and enhanced recharge) are more acceptable because they do not emphasize reduction in present water use. However, when supply augmentation measures take the dimension of mega-water transfer schemes, the propositions become highly political and contentious as have India's plans to link Himalayan and peninsular rivers.

When supply augmentation measures take the dimension of mega-water transfer schemes, the propositions become highly political and contentious

Managing demand for groundwater

Many Middle East and North Africa countries, which developed intensive groundwater-irrigated agriculture based on nonrenewable groundwater, have begun to save their aquifers for the more pressing drinking water needs of present and future generations. Saudi Arabia expanded wheat irrigation during the 1970s, eventually becoming an exporter. In 1992 Saudi Arabia spent $2 billion to subsidize local production of 4 million metric tons of wheat, which it could have bought at a fifth of the cost in the global wheat market (Postel 1992).

box 10.2 | Interbasin water transfer in the San Joaquin Valley of California

In the San Joaquin Valley of California groundwater irrigation was managed to create a tax base that would support water imports. Thanks to rapid agricultural growth, by the early 1950s well irrigators were pumping more than 1.2 billion cubic meters of water. Percolation of irrigation water became the main source of recharge, exceeding natural recharge by 40 times. The drawdown to 30–60 meters changed the direction of water flow in the confined zone, and pumping lifts increased to 250 meters in many areas. Land subsidence soon emerged as a widespread problem. These costs justified the import of water through the California Aqueduct. After 1967 surface water irrigation increased substantially, and hydraulic head increased by 30–100 meters. Throughout the area the recovery in potentiometric surface from 1967 to 1984 was nearly half the drawdown that occurred from predevelopment years to 1967. Increased recharge with surface irrigation and reduced groundwater draft raised water tables to less than 1.5 meters in some parts, causing drainage problems. A regional tile drain installed in 1988 over a 150 square kilometer area lowered the water table but also diverted water that could have been used to increase recharge.

Source: Llamas, Back, and Margat 1992.

More recently, Saudi Arabia has successfully reduced wheat irrigation through administrative controls (Abderrahman 2001). Oman has similarly used stringent administrative regulation to control groundwater withdrawals for irrigation. And Iran has banned new irrigation tubewells in a third of its plains for nearly a decade (Hekmat 2002). Mexico and Spain's experience with a communitarian model of groundwater management is described in box 10.3. Some efforts to manage demand for groundwater in Asia are discussed in box 10.4.

Elsewhere—as in Jordan, Syria, and Yemen—efforts to regulate groundwater irrigation have been made but have had limited success. However, the urgency of the need to do so is widely accepted. Algeria, Morocco, and Tunisia depend on renewable groundwater, but their well numbers have increased at South Asian rates, leading to serious problems of contamination and saline water intrusion (Bahri 2002).

Moving toward precision irrigation and water-saving technologies

Water-saving technologies—drip and sprinkler systems, pipes rather than open furrows to transport water from well-heads, mulch, and the like—are often recommended to ease pressure on groundwater. However, many researchers question these technologies. First, water leakage is not always a loss but may be a source for other users downstream. Second, only cutting down on excessive evaporation (such as evaporation from bare soil, open canals, and water-logged areas) holds any promise of alleviating groundwater declines. If farmers use the freed water to expand irrigation, the net effect may actually be more evapotranspiration (and groundwater decline) rather than relief. Kendy (2003) holds that only cutting down on

box 10.3 | Groundwater management in Mexico and Spain

Mexico and Spain have recently experimented with a communitarian model of groundwater management. The underlying premise is that organized and empowered groundwater users will mobilize their collective strength to monitor groundwater behavior and take the steps necessary to protect the resource and ensure its long-term sustainability. Mexico's 1993 Water Law declared water to be federal property, and a more recent Supreme Court verdict applied that provision to groundwater. The Mexican National Water Commission has been registering all irrigation wells and issuing concessions (permits) to farmers to withdraw specified quotas of groundwater. The commission has also organized groundwater users in aquiferwide Technical Committees for Groundwater Management (Marin 2005, personal communication).

Spain has tried a similar strategy. Spanish authorities have formed groundwater user associations to manage resources at the local level. A new mandate from the EU Framework Directive to protect groundwater has given these associations more significance.

However, in Mexico, Spain, and elsewhere the impact of these strategies on groundwater conservation and protection seems uncertain. If anything, the impact is perverse in some regions. In Mexico, for instance, a recent use-it-or-lose-it move by the National Water Commission to withdraw unused portions of groundwater quotas encouraged farmers to pump more groundwater than they would have otherwise, lest they lose their quota (Marin 2005, personal communication). In Spain studies show that most groundwater user associations are defunct and the water law is widely bypassed (Lopez and Llamas 1999).

box 10.4 Groundwater management in Asia

If countries in the industrial agricultural systems category (see table 10.3) find sustainable groundwater management difficult, countries in the smallholder farming system category—including those in South Asia—have not even begun to seriously address the problem. China has done more, but it will take time before its initiatives bear fruit (Shah, Giordano, and Wang 2004). Mexico's model is being held out as a panacea to smallholder farming system countries, but there is no evidence that this model has helped Mexico move toward sustainability (see box 10.3). Mexico's efforts need to produce better results before they can be held out as a model for other groundwater-using countries to follow.

Cross-country analysis suggests that governing the groundwater economy in a sustainable manner concerns not only the hydrogeology of aquifers but also the larger political and social institutions of a country. How countries respond to the challenge of sustainable management of groundwater depends on factors related to the context of each country. These factors can have a decisive impact on whether an approach that has worked in one country will work in another with a different context.

Consider attempts to ban tubewells. Mexico has been trying to ban new tubewells in its central plains for 50 years and has yet to succeed. China has a large number of tubewells scattered over a vast countryside. Chances are that over the coming decade, the government will be able not only to bring them within the ambit of its permit system but also to influence their operation. Accomplishing the same thing in India or Pakistan will remain unrealistic for a long time because of the countries' political structures and systems. The Indian states of Maharashtra and Uttar Pradesh already have elaborate legislation to control groundwater overdraft, but implementation has been patchy (Phansalkar and Kher 2003; Narayana and Scott 2004).

irrigated farming in stressed areas, as witnessed in parts of the United States, will be effective. Precision strategies save water when they reduce evaporation, when they prevent water from becoming salinized or polluted, or when the percolation does not readily recharge aquifers.

Microirrigation technologies are likely to increase in popularity all the same. Many countries, such as India, however, are less concerned about saving water than saving energy. Energy subsidies make up a large proportion of government budgets. Microirrigation definitely improves energy efficiency in groundwater irrigation if not water efficiency. Moreover, worldwide, farmers take to microirrigation technologies not so much to save water but to improve crop yields and quality. This is beginning to become evident among farmers in Asia as well. Microirrigation systems used to be capital intensive because they included sophisticated control mechanisms appropriate for large farms. Nongovernmental organizations and irrigation equipment companies are now discovering that Asian farms can do without these expensive mechanisms, and as a result the costs of microirrigation systems are dropping to a fraction of what they were a decade ago. Many nongovernmental organizations are promoting low-cost microirrigation systems to poor women farmers in Africa and Asia. Again, the key idea is not so much to save groundwater but to improve livelihoods.

Water-saving crops and technologies. Though controversial, a big breakthrough in water saving is promised by the system of rice intensification, a package of agronomic practices that suggest that the rice plant can withstand flooding but does not need it to thrive.

Whether the system of rice intensification results in significant real water savings is debatable (see chapter 14 on rice). But many governments—including those in China and the south Indian states of Andhra Pradesh, Karnataka, and Tamil Nadu—are promoting the system as an answer to growing water stress in rice systems (Jothimani and Thiyagarajan 2005; Satyanarayana 2005). A real issue that the system tackles is the energy costs of groundwater irrigation. In rice growing regions such as Bangladesh, West Bengal, and Assam—where an agrarian revolution of sorts was ushered in by groundwater irrigation of boro rice with diesel pumps—an increase in diesel prices and a drop in rice prices have led to a precipitous decline in the area growing boro rice. The system of rice intensification offers an opportunity for its revival by curtailing irrigation costs. Zero tillage, alternate wet and dry irrigation of paddy, and other such agronomic practices also hold promise for water saving in field crops.

> Precision strategies save water when they reduce evaporation, when they prevent water from becoming salinized or polluted, or when the percolation does not readily recharge aquifers.

Other examples of cropping pattern changes that save groundwater are replacement of irrigated rice with rainfed maize and of irrigated maize with Bt cotton on a large scale in many parts of the North China plains. In Liaoning Province, for example, rising costs of electricity and chemical fertilizers and falling international rice prices have resulted in large-scale substitution of groundwater-irrigated rice with rainfed maize, leading to substantial recovery in groundwater levels (Shah, Giordano, and Wang 2004).

Crop diversification and more cash per drop. In the groundwater-irrigated North China plains there has been a large-scale shift from maize to cotton, especially Bt cotton, which grows extremely well under drip irrigation and polythene mulch. Just as pronounced is the unprecedented shift to production of high-value fruits and vegetables for sale in both domestic and export markets. This production is also especially well supported by groundwater. In many groundwater-irrigated areas of India the shift is evident in the rapid expansion of dairy production systems under groundwater use. In groundwater-stressed Andhra Pradesh the value of dairy production has surpassed the combined value of all crops in recent years (Tukker 2005, personal communication). Likewise, in groundwater-stressed North Gujarat dairying has expanded rapidly under groundwater-irrigated fodder crops, becoming the mainstay of rural livelihood systems (Kumar and Singh 2004). In Tamil Nadu's groundwater-stressed areas rice paddy is giving way to exotic crops such as vanilla. Whether these shifts toward value-added farming will ease the pressure on groundwater is uncertain, but they will help improve livelihoods and raise income per cubic meter of groundwater use.

Occupational diversification. Groundwater stress in smallholder farming systems essentially reflects population pressure on agriculture. In some arid or semiarid parts of India where intensive groundwater has sustained high population pressures, declining groundwater availability and reliability have forced farmers out of farming. The transition may also be planned, in the sense that farmers intentionally keep overdrafting the aquifers to build sufficient wealth from their fields to support their children's education and permanent transition and settlement in the cities (Moench and Dixit 2004). In the medium to long run transferring the population to the nonfarm sector will ease pressure on land and groundwater.

* * *

In conclusion, in regions of the world where groundwater use in agriculture is expected to grow, people will have to be a part of the solution. No resource management strategy will work unless it is embraced by millions of users. As Noam Chomsky, one of the great living philosophers, said:

> At this stage of history either one of two things is possible. Either the general population will take control of its own destiny and will concern itself with community interests, guided by values of solidarity and sympathy, and concern for others; or alternatively there will be no destiny for anyone to control (*Manufacturing Consent: Noam Chomsky and the Media* 2:40:53).

Reviewers

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Notes

1. There are other data sets compiled by private researchers often under the aegis of international organizations. Margat (2005, personal communication) has compiled estimates of groundwater irrigated areas. They use mostly data from the Food and Agriculture Organization's (FAO) AQUASTAT database, with refinements or updates for specific countries. Zekster and Everett's (2004) report for the United Nations Educational, Scientific and Cultural Organization's (UNESCO) International Hydrological Programme is another, but it relies solely on national government sources, which are also the sources for FAO's AQUASTAT.

2. AQUASTAT lacks data on groundwater-irrigated areas. Since leaving out China from this analysis would distort the picture greatly, we have used the estimate of 8.46 million ha provided in China National Bureau of Statistics (2002). However, Wang and others (2006b) cite a Chinese government source that suggests that groundwater-irrigated area in China was about 15 million ha in 2000. They go on to estimate, based on their own large-scale survey, that this figure may be as high as 23 million ha.

3. The International Water Management Institute's (IWMI) global irrigated area map (Thenkabail and others 2006), which is based on remote sensing data, estimated gross global irrigated area to be 480 million ha in 1999, far above FAO's more recent estimates of 257–280 million ha. According to the IWMI map, groundwater gets involved—either as the sole source of irrigation or in conjunctive use mode—in 132 million ha of global gross irrigated area, which is over 50% higher than FAO estimates of groundwater irrigated area.

4. These figures do not include the fadama and bas fonds areas, since these styles of irrigation are not classified as equipped irrigated areas but as areas under water management.

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