The Global Groundwater Situation: Overview of Opportunities and Challenges

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The Groundwater Challenge

Throughout the world, regions that have sustainable groundwater balance are shrinking by the day. Three problems dominate groundwater use: *depletion* due to overdraft; waterlogging and *salinization* due mostly to inadequate drainage and insufficient conjunctive use; and *pollution* due to agricultural, industrial and other human activities. In regions of the world, especially with high population density, dynamic tube-well-irrigated agriculture and insufficient surface water, many consequences of groundwater overdevelopment are becoming increasingly evident. The most common symptom is secular decline in water tables. In North China's Henan province, China's largest, where some 2 million hectares—52 percent of irrigated lands—are served by tube wells, water table monitoring data on 358 observation wells encompassing 75,000 km^2 showed water table declines of 0.75–3.68 meters during 1975–87. In the Changzhou prefecture of Hebei province—where 76,800 wells irrigate 0.29 million hectares—37 percent of the irrigated area—the area covered by saline water increased by 9.1 percent during 1980–90 (Lunzhang 1994). In the Fuyang river basin of North China where IWMI has been studying basin institutions, surface water supplies to agriculture have been drastically curtailed over a 20-year period for meeting industrial needs; farmers have responded by resorting to groundwater irrigation; the number of tube wells in the basin has increased to some 91,000, mostly during the 1970s and the water table has fallen from 8 to 50 meters during 1967–2000. Aquifers in the Fuyang basin are under double assault: farmers are depleting the lower aquifers and industries are polluting the upper ones.

Groundwater problems in West and South Asia are as pernicious as or even worse than those in China. A groundwater basket case is Yemen. A recent World-Bank memorandum on water management in Yemen noted: "the problem of groundwater mining represents a fundamental threat to the wellbeing of the Yemeni people. In the highland plains, for example, abstraction is estimated to exceed recharge by 400 percent" (Briscoe 1999). Yemen is probably the only country where groundwater abstraction exceeds the recharge for the country as a whole (ibid.). Mexico's aquifers too are amongst the most overdeveloped; IWMI researchers based in Guanajuato State, one of Mexico's agriculturally dynamic regions, found water tables in 10 aquifers they studied declining at average annual rates of 1.79–3.3 meters/year during recent years (Wester, Pimentel, Scott 1999,9). The situation in South Asia is no better. In western, northwestern and peninsular India and Pakistan, where in recent times, over a million irrigation wells have got added every year, groundwater withdrawal exceeds annual recharge in vast areas that are growing every year. Where this process has been rapid, the consequences are serious and visible. In the two Punjabs, Haryana and Western Rajasthan, the main consequence has been salinity; in North Gujarat and Southern Rajasthan, it is fluoride contamination of groundwater; in hard-rock Southern India, it is declining well yields and increasing pumping costs arising from competitive deepening of wells. In West Bengal and western Bangladesh, the consequence is arsenic contamination (Khan 1994). In coastal areas, the most serious consequence of intensified pumping of groundwater for irrigation is saline ingress into coastal aquifers. All these problems will impair the region's capacity to feed its growing population. According to David Seckler, IWMI's Director General, a quarter of India's harvest may well be at risk from groundwater depletion.

Unplanned groundwater exploitation can wreak havoc on fragile ecologies such as wetlands. A good example of how groundwater overexploitation can ruin ecologies is offered by the Azraq Oasis in the heart of the Jordanian *Badia*. The Azraq, a Ramsar wetland of over 7,500 hectares, has provided a natural habitat for numerous, unique, indigenous, aquatic and terrestrial species; and the oasis was acclaimed internationally as a major station for migratory birds until it dried up completely as a result of groundwater overexploitation upstream through mechanical pumps for irrigation and for feeding the city of Aman. Overdraft resulted in the decline of shallow water tables from 2.5 to 7 meters during the 1980s drying up the natural springs whose supply to the oasis fell from over 10 mm^3 in 1981 to less than 1 mm^3 in 1991. The result was the collapse of the whole ecosystem, increase in the salinity of groundwater from 1,200 to 3,000 ppm, and the decline of the tourist economy around the oasis (Fariz and Hatough-Bouran 1996).

Groundwater is also emerging as a critical issue for cities and towns around the world. At the heart of the urban groundwater problem is population density; cities just do not have a large enough recharge area to support the needs of their inhabitants on a sustainable basis. Some three hundred of China's densely populated large and medium cities—dependent on groundwater—face acute water shortages (www.facingthefuture.org) and have to look outward for their water needs. Things in Beijing have gone so bad that farmers in the neighboring hinterland have been prohibited from using water from local reservoirs for irrigation (ibid.). The city of Izmir in Western Turkey is fed from well fields from the neighboring district of Manisa whose citizens have become increasingly restive about it. In South Asia, the urban groundwater scene is reaching a melting point: large cities like Ahmedabad and Jodhpur in Western India and Chennai in the South Indian state of Tamilnadu support thriving private groundwater businesses that draw water from tube wells in the neighboring hinterlands for supplies to high-income residential areas because groundwater tables in the cities are falling at a rate of 7–10 ft./yr. Bangkok, Jakarta and Mexico city have been facing acute problems of land subsidence because of groundwater depletion. The Department of Water Affairs and Forestry of the Government of South Africa estimates that more than four hundred of its towns and cities depend on groundwater for domestic supplies; and many near the coast—including Alexandria, Jeffery's Bay, Kleinmond, Bushmansrivemouth, and Kenton-on-Sea, St. Fransis Bay, Plettenberg Bay, Atlantis, Port Alfred, Port St. Johns—already run the risk of saline intrusion (Morris 1997). Urban industrialization is also a major contributor to urban groundwater problems; in South Korea's industrial cities such as Seoul, Pusan and Daegu, water tables have dropped by 10–50 meters over a 30-year period due to industrial pumping. In the Cheju island, seawater intrusion in coastal aquifer has been the direct result of industrial pumping of groundwater (Lee 1994).

Besides depletion, waterlogging and the pollution of aquifers through human activity constitute another major groundwater challenge. Waterlogged areas in India are estimated at 6 million hectares ; in 12 major irrigation projects with a design command of 11 million hectares, 2 million hectares were waterlogged, and another million hectares salinized (Mudrakartha 1999). An Irrigation Commission set up by the Government of India places canal irrigated areas suffering from waterlogging and salinization at 6 million in the early 1970s; these have increased substantially since then. In Pakistan, rising water tables and groundwater salinity are among the most important issues in the Indus basin. Where groundwater quality is good, groundwater draft in waterlogged areas offers a big win-win opportunity. The SCARP tube well program in Pakistan and a similar earlier program of public tube wells in waterlogged areas on the Satlaj-Yamuna canal to pump water for irrigation or to augment canal supplies seemed promising but have proved institutionally unsustainable (Moshabbir and Khan 1994). In many arid and semiarid areas, however, salinity comes with waterlogging that complicates matters. Desalinizing brackish water though cheaper than desalinizing seawater is yet to become a mainstream option. Farmers in west Haryana have evolved homegrown formulas for blending saline groundwater with good quality canal irrigation; these seem to be effective but need close examination.

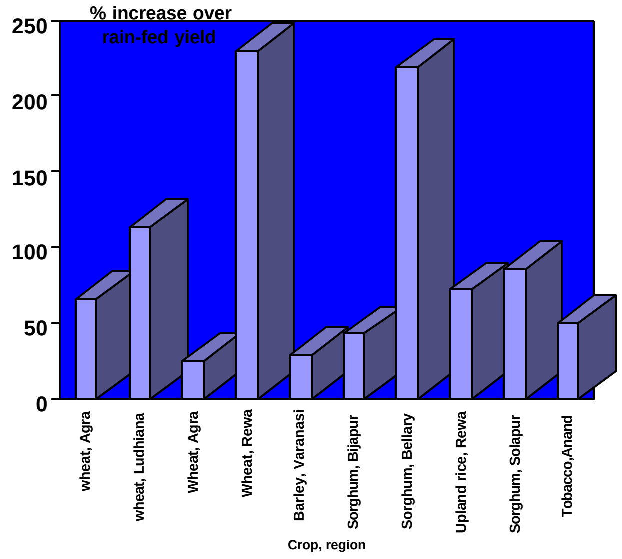
Aquifer pollution—from both point and nonpoint sources—is becoming extensive worldwide. In the Gediz basin of Anatolia, Turkey, nonpoint pollutants—mostly agrochemicals—have polluted the groundwater and the river downstream so badly that cities like Izmir, and strawberry orchard owners in Menemen, would rather pump groundwater than use the river water. In North Arcot district in the Indian State of Tamilnadu, coconut water contained 0.2 percent of residual chromium derived from chrome-tanning process-based tanneries that contaminated the groundwater (K. Sarabhai in foreword to Mudrakartha 1999). In the west Indian State of Gujarat, groundwater pollution by textile processing and the rapidly growing chemical industry earned such notoriety that, in 1998, acting *suo moto,* the State's High Court ordered an entire industrial estate—housing over 1,200 manufacturing units, 70 percent of them chemical—closed, pending the establishment of a wastewater treatment and disposal system.

Opportunity

Ironically, at the heart of all these problems the world faces are the unique advantages that groundwater has and the opportunity this offers for human development. Groundwater is accessible to a large number of users; it can provide cheap, convenient, individual supplies; it is generally less capital-intensive to develop, and does not depend upon mega-water projects. Groundwater development is also largely self-financing; its largely private development and use ensure automatic cost recovery. When it is not degraded by human intervention, the major advantage of groundwater is its high microbiological quality, arising from its situation below ground and the natural protection this affords (Calow et al. 1997, 242). Compared to surface water, which is flashy in nature, groundwater offers better insurance against drought because of the long lag between changes in recharge and responses in groundwater levels and well yields (Carter and Howsam 1994).

Irrigation with groundwater is also generally more productive compared to much surface water irrigation; groundwater is produced at the point of use, needing little transport; it offers individual farmer irrigation "on demand" that few surface systems can offer; and because its use entails significant incremental cost of lift, farmers tend to economize on its use and maximise application efficiency. Evidence in India suggests that crop yield/m^3 on groundwater-irrigated farms tends to be 1.2–3 times higher than on surface-water-irrigated farms (Dhawan 1989,167). Similar evidence is available from other parts of the world as well (see, Hernandez-Mora, Llamas, and Martinez-Cortina 1999 for a comparative study in Andalucia, Northern Spain). Groundwater users in South Asia often use only a small fraction of scientifically recommended water requirements; rather than aiming at full irrigated yields, they use sparse, life-saving irrigation to obtain whopping increases over rain-fed yields (see figure 1). This is because of high marginal cost of groundwater use; some of the poorest irrigators in South Asia—who purchase pump irrigation from well-owners—commonly pay US10–14 cents/m^3 of water compared to a fraction of a cent paid by canal irrigators. Finally, compared to large surface systems whose design is driven by topography and hydraulics, groundwater development is often much more amenable to poverty-targeting. No wonder, then, that in developing countries of Asia and Africa, groundwater development has become the central element of livelihood creation programs for the poor (Shah 1993 for India; Kahnert and Levine 1993 for the GBM basin; Calow et al. 1997 for Africa).

Figure 1. Yield Impact of life-saving 5 cm irrigation on rain-fed crops in India (Dhawan 1989, after Singh and Vijaylakshmi 1987).



Groundwater and Rural Poverty

In the Ganga-Brahmaputra basin of South Asia as well as in much of Africa, groundwater irrigation offers a big opportunity for enhancing the livelihoods of the poor. In the former, the population density and concentrated rural poverty are high; but the untapped resource is large too.[1] In many parts of Africa, the resource is modest and largely undeveloped; but the population density is low, too. In both these regions,

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[1] Apart from Amazon, few rivers in the world have as high a ratio of average runoff to the area of the basin as the Ganga-Brahmputra basin has, with an average runoff of 1,400 km^3 for a basin area of 1.73 million km^2 Shiklomanov 1993, 16.

the central challenge is to put the pump into the hands of the poor. David Seckler, Director General of the International Water Management Institute, has suggested that few irrigation technologies have had as wide-ranging and profound an impact on the lives of the people as the small mechanical pump; and this becomes evident in the Ganga basin and in sub-Saharan Africa where poor households could transform their farming and their livelihoods if only they could lay their hands on a pump. Indeed, much recent evidence links the agricultural dynamism in parts of Bangladesh, West Bengal and Eastern India to the growing offtake of pumps and tube wells by private farmers (see, for example, Rogaly, Harris-White, and Bose 1999). But the poorest in these regions are often too poor to save enough to buy a pump; further, often, their holdings are too small to make a mechanical pump a viable investment.

In South Asia, rapid groundwater development has supported a booming pump industry which, in India, has grown at a compound rate of 20 percent since 1982; this growth is characterized by both economies of scale and intense competition. As a result, South Asia's rural poor have benefited from low costs of pumps and borings. In the Sahel, in contrast, pump irrigation development is so slow and limited that costs of pumps and washbores are high and quite beyond the reach of smallholders. Researchers from UK's Cranfield university found that "In Africa the cost of a borehole drilled by a truck-mounted rig can be extremely high in absolute terms (f 3,000-6,000) as well as in relative terms (10–20 times the cost of the pump and many times the cost of well drilling in Asia. High unit costs mean that too few wells are drilled and communities and farmers remain dependent on international aid programs for this form of infrastructure development" (Carter 1999). In Nigeria, for example, the groundwater irrigation potential is estimated at 870,000 for washbores and tube wells; but the actual numbers in use at the turn of the 1990s were a few thousand. In West Africa as a whole, thus, "The [groundwater] potential remains almost untapped; only 0.2 percent of recoverable safe yield and 0.02 percent of the groundwater held in reserve is presently used. Main reasons that militate against groundwater exploitation for agricultural production are the [high] cost of drilling wells and lifting water onto the land." (Sonou1994, 73).

There is therefore enormous room for institutional and technological innovations that can put groundwater irrigation at the service of the poor. In South Asia, emergence and spread of water markets have helped improve poor people's access to groundwater. Tube wells owned and operated by groups of poor farmers also offer possibilities. Micro-diesel pumps made in China have become extremely popular with smallholders in Bangladesh because they cost less to buy as well as to run compared to 5-hp diesel pumps that have become industry-standard in India. Among the most exciting are innovations in manual irrigation technologies; the treadle pump—selling as *Krishak Bandhu* (Farmer's Friend) in South Asia and "Money Maker" in Africa—costs US$12–25 a piece and can be operated by anyone including children. This has become hugely popular in Bangladesh where there already are over a million sold; it is spreading to Eastern India and Nepal terai where water tables are in the range of 2–5 m. Treadle pumps are particularly popular with vegetable growers who combine a small area of land with large volumes of disguisedly unemployed family labor to generate disproportionately large cash incomes (Shah et al. 2000). Equally popular in this segment are likely to be the new range of low-cost bucket- and drum-based drip irrigation technologies that have recently begun coming into the market. IWMI is currently investigating what might well be the biggest opportunity for irrigation against rural poverty in the region: exploring ways of bridging the gap between the manual pump—which appeals primarily to the vegetable growers with tiny garden plots—and the 5-hp diesel pump, the industry standard, which is too big and costly for most marginal farmers.

If underdeveloped groundwater in the Ganga basin and parts of Africa presents an opportunity for the poor, groundwater depletion and contamination elsewhere hold out a big threat for them. Depletion has far-reaching social as well as environmental dimensions, and leave immiserising aftereffects on all, but, often, on poor more than on the rich. In South Asia, when muscle-driven traditional water lifts went out of business with the onslaught of tube wells, it was the poor who got hit the hardest. New siting and licensing policies reinforce the rights of the early tube well owners and exclude the late comers, who typically are the poor. One of the most serious ill-effects of depletion is from seawater intrusion in coastal aquifers as in Egypt, Turkey, China and India. In the Saurashtra coast of the West Indian state of Gujarat, sustained overpumping by private farming communities during the 1960s and 1970s generated previously unseen prosperity, earning the coastal strip the name of "Green Creeper." Rapid seawater intrusion in coastal aquifers—which extended from 1 km to 7 km inland in a decade, however, caused similarly rapid collapse of the region’s unsustainably bloated tube well economy. 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 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. Many kept eking out a living by selling tender coconuts; but this too became difficult as coconuts shrank in size and contained saline water. In recent years, tens of villages get depopulated every year as those left behind proceed town-ward to join the ranks of the wage laborers (Shah 1993).

Availability and Use: The Fallacy of Aggregation

Central to appreciating the global groundwater situation then is the coexistence of regions with undeveloped resources and those with overdeveloped resources, and the socioeconomic dynamic that has relentlessly impelled the former to shrink and the latter to expand. Equally important is the fallacy of aggregation: in aggregate terms, at the global and even national level, groundwater availability appears far in excess of present use. The annual groundwater use for the world as a whole can be placed at 750–800 km^3, which value appears modest compared to overall water availability. But an overwhelming majority of the world’s cities and towns depend on groundwater for municipal water supplies. Half of the US population draws its domestic water supply from groundwater (Morris 1997). Groundwater is also critical in supplying the industrial water demand in most countries. In some of the most populous and poverty-stricken regions of the world—particularly in South Asia—groundwater has emerged at the center-stage of the food-agricultural economy. In India, for example, some 60 percent of the irrigated food grain production now depends on irrigation from groundwater wells. Between India, China, the US and Pakistan, some 325 km^3 of groundwater is used every year; the 14 countries included in figure 2 use some 520 km^3 (FAO’s AQUASTAT); over 35 countries of the world use more than 1 km^3 of groundwater annually (Llamas, Back, and Margat 1992).

Figure 2. Groundwater use in selected countries in the 1980s
(Llamas, Back, and Margat 1992,4; and Takeuchi and Murthy 1994,14).

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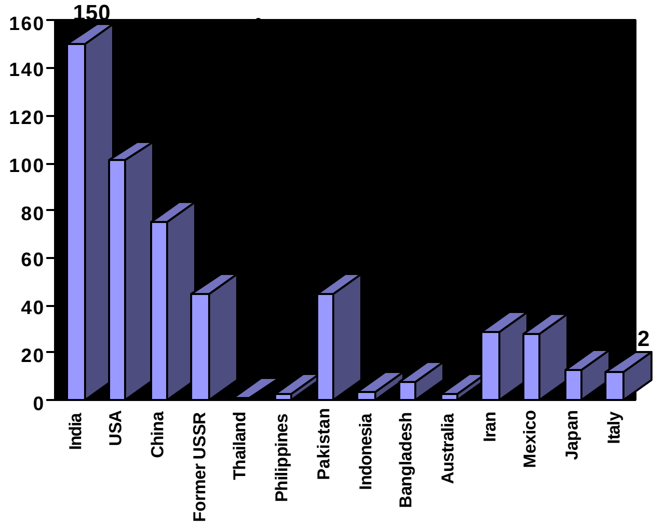

In comparison, world's aggregate groundwater resources appear abundant. Groundwater—both stock and flow[2]—constitutes over two-third of the world's freshwater resource, if we exclude glaciers and permanent snow cover (Shiklomanov 1993,13; Dutt 1987). Even if 8 percent of the 33,000 km^3 (Postel 1999)[3] floodwater that runs off to the oceans annually recharge the groundwater, we have a renewable supply of over 2,500 km^3 of groundwater annually—which seems several times more than the world uses today. This tallies with the picture that emerges from national estimates of groundwater availability and use. According to FAO's AQUASTAT, the Russian Federation uses less than 5 percent of its 900 km^3 of annual recharge; West Africa uses less than 1 percent; China's renewable groundwater supply is estimated at over 800 km^3; but it uses just around 70; even India, which has serious overexploitation problems uses only a third of her estimated annual recharge of some 450 km^3. Yet, groundwater depletion and the host of associated problems pose one of the most daunting challenges that the world faces in the water sector.

This is because of spatial imbalances in the occurrence of groundwater and the pattern of demand for it. In the bygone millenia, human settlements formed around abundant water bodies; but this seems no longer the case today, at least vis-à-vis groundwater. South China has 68 percent of China's total groundwater recharge, 54 percent of population but only 36 percent of farmlands, and is therefore able to use only a small fraction of its groundwater resources. In contrast, North China has only 31 percent of China's groundwater, but 46 percent of the population and 64 percent of farmlands and is facing serious problems of groundwater overexploitation (Kramer and Zhu 1988**;** Lunzhang 1994). Similarly, the Ganga-Meghna-Brahmaputra basin—home to some 500 million of the world's poorest people—faces acute problems of waterlogging and flood-proneness despite the addition of over 3 million to its stock of

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[2] Estimated variously to be 8,200–60,000 km^3 (Gleick 1993,120).

[3] The total river runoff however has been placed at 46,770 km^3 by Shiklomanov (1993, 15).

irrigation tube wells over the past 50 years. One might even argue that pre-monsoonal water tables in much of the basin are unlikely to fall by more than 1.5–2 meters even if the density of irrigation wells were doubled and, in addition, 20–25 km^3 of the 1,400 km^3 of the Ganga-Brahmaputra flood discharge were stored for augmenting the Ganga's low-flows. If anything, increased tube well irrigation would alleviate the endemic waterlogging and flood-proneness that impose enormous welfare costs on the people of the region (Centre for Science and Environment 1991; Shah 2000). But peninsular India and western India—including the Punjab and Haryana, India's breadbasket—have faced massive problems of groundwater overdevelopment. Water tables in these regions have dropped beyond the reach of muscle-driven water lifts used by farmers for centuries for protective irrigation. In North Gujarat, bullock-bailers could lift groundwater for irrigation barely 30 years ago because water levels in wells were 10–15 meters; but today, tube wells reach out to a depth of 400–450 meters to get economic discharge; and the 35–75-hp pumps needed for lifting water from such depths cost so much that farmers in the region have evolved the institution of tube well companies to share the costs and the risks of these irrigation investments (Shah and Bhattacharya 1993).

Responses to Groundwater Depletion

By far the most serious groundwater challenge facing the world, then, is not in developing the resource but in its sustainable management. As problems of groundwater depletion—and its deleterious consequences—have surfaced in different parts of the world, a variety of responses have been forged to mitigate or even reverse these. The standard reasoning is that even after 800,000 big and small dams around the world, the reservoirs can capture and store no more than a fifth of the rainwater, the bulk of the remainder still running off to the seas. India has built more than its share of the world's dams but 1,150 km^3 of its rainwater precipitation still run off to the seas annually in the form of "rejected recharge" (INCID 1999). If a fraction of this could be stored underground by reducing the velocity of the runoff and providing time for recharge, groundwater supplies could be enhanced significantly. But this presumes *active* aquifer management where planned drawdown of the water table in the pre-monsoonal dry months is an important element of the strategy for enhancing recharge from monsoonal rainwater as well as from irrigation return flows. In the developing world, however, such active aquifer management is still a far cry. In what is being done, several approaches stand out.

Recharge with Imported Surface Water

Some of these experiments show successful efforts to retrieve valuable ecologies-at-risk. In the Azrak Oasis of central Jordan that we discussed in a previous section, conventional measures to regain the ecology—stopping water supply to Aman or cessation of irrigation—were politically infeasible. However, a UNDP-supported project reverse-pumped into the epicenter of the lakes 1.5–2 million m^3 of groundwater imported from a water-surplus well field. Along with a number of supportive measures—such as cleaning of springs and rehabilitation, the strategy was able to retrieve the Arzaq wetland pretty much to its original position; birds came back; and Azrak's tourist economy too apparently bounced back to life (Fariz and Hatough-Bouran 1996). Similar examples at the basin level can be found but only in developed countries. One such example is the San Joaquin valley of California, where groundwater irrigation was managed to create a tax base that would support the import of water. With rapid agricultural growth, by the early 1950s, more than 1.2 billion m^3 of water were being pumped by well-irrigators. And percolation of irrigation water became the main source of recharge and exceeded natural recharge by 40 times. The drawdown to 30–60 meters caused a change in the direction of water flow in the confined zone; and pumping lifts increased to 250 million in many parts and land subsidence emerged as a widespread problem. These costs justified the import of water through the California Aqueduct. After 1967, surface irrigation increased significantly, and hydraulic head declined by 30–100 meters. Throughout the area, the recovery in potentiometric surface from 1967 to 1984 was nearly one-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-km^2 area lowered water table but also diverted water that could have been used to increase recharge (Llama, Back, and Margat 1992, 6–7). China is similarly planning trans-basin diversions from the Yangtzi in the water-surplus south to the water-short Yellow river basin in the north (Keller, Sakthivadivel, and Seckler 2000). India has talked about a garland canal to link Himalayan rivers with Cauveri and other South Indian rivers; but these have remained at the ideas' level.

Recharge with Rainwater

Long-distance transport of large quantities of water is however often problematic besides being expensive. In many parts of the world, especially in South Asia, increasing stress is being placed on *in situ* rainwater harvesting and recharge. In the monsoonal regions, this approach seems particularly important because, as in India, the bulk of the year’s rainfall is received in some 100 hours of heavy downpour, providing little time for recharging the groundwater (Keller, Sakthivadivel, and Seckler 2000). Moreover, the relationship between the recharge area, recharge rate and the extent of sustainable groundwater irrigation is now becoming increasingly important. A study of groundwater irrigation in the northern Anuradhapura district of Sri Lanka showed that for every acre of groundwater irrigated area, 34 and 37 acres of recharge area are needed for sustainability in upland and lowland areas, respectively (Premanath and Liyanapatabendi 1994). As groundwater irrigation increases, this ratio comes under pressure and the only way out is to increase the recharge rates.

The age-old traditions and structures for rainwater harvesting in some of the water-scarce regions of Asia have fallen into disuse and are now attracting renewed attention. If estimates are to be believed, China has some 7 million ponds, which have potential for water-harvesting and recharge. And in South India where the three states of Karnataka, Andhra Pradesh and Tamilnadu have over 200,000 tanks, a strategy that has been widely recommended is to transforming these into recharge tanks by filling them up with canal water (Kulandaivelu and Jayachandran 1990; Reddy, Rao, and Prakasam 1990). In the Kurnool irrigation system of Andhra Pradesh, 9 percolation ponds and 7 check dams constructed in an experimental recharge project increased the duration of spring-flow from 75 to 207 days; and postmonsoonal water table rose by 2.5 meters (ibid.). India's Central Groundwater Board too has been carrying out recharge experiments at several sites. Tarun Bharat Sangh and Pradan, two local NGOs in the Alwar district of western Rajasthan, whose work IWMI has been studying, have helped local communities to rehabilitate centuries-old tanks (known locally as *johads* or *paals)* with dramatic impact on groundwater recharge and revival of dried-up springs and rivulets in a 6,500–km^2.

In the western region of India, hit hardest by groundwater depletion, however, people have figured out that they have no time for experiments or for governmental action. Catalyzed by spiritual Hindu organizations—such as the *Swadhyaya Pariwar* and *Swaminarayana Sampradaya*—and supported by numerous local NGOs, people have spontaneously created a massive well-recharge movement based on the principle "water on your roof, stays on your roof; water on your field stays on your field; and water on your village, stays in your village." People have modified some 300,000 wells—open and bore—to divert rainwater to them; they have also constructed thousands of ponds, check dams and other rainwater-harvesting and recharge structures on the self-help principle to keep the rainwater from gushing into the Arabian sea (Shah 2000). While IWMI plans systematic studies of the impact of the movement and the popular science of well-recharge that has emerged as a result of farmers' experiments, indicative evidence available suggests that for regions critically affected by groundwater depletion, only mass popular action on a regional scale may be adequate to meet the challenge of depletion.

India has begun to take rainwater harvesting and groundwater recharge seriously at all levels. These are at the heart of its massive Integrated Watershed Development Program, which provides public resources to local communities for treatment of watershed catchment areas and for constructing rainwater-harvesting and recharge structures. Trends during the 1990s also suggest a progressive shift of budgetary allocations from irrigation development to water-harvesting and recharge. One indication of the seriousness assigned to an issue by Indian leadership is the message delivered by the Prime Minister to the citizens on the Republic Day; and on 26th January last, India's Millenium Republic Day, the nation's Prime Minister and the Water Resources Minister went to the people with a full-page story espousing the benefits and criticality of groundwater recharge.

Vegetative Treatment of the Catchment

Vegetative cover on the free catchment of a basin has proven to be a problem as well as an aid to groundwater recharge. For example, some 10 million hectares of land in South Africa are infested by alien weeds—Acacia spp (especially, mearnsii, and saligna and longifolia), pinus spp, eucalyptus spp, prosopis spp (Guy Preston 2000) —that use up 3.3 billion m^3 more water—almost 7 percent of the country's total runoff—than the indigenous plants it replaced; the weed infestation is considered to be a major threat to groundwater recharge. A special long-term program by the South African Government's Department of Water Affairs and Forestry, called "Working for Water" to remove the alien weeds, employs some 42,000 people at its peak every year, but it will take 20 years or longer to complete the job. In contrast, there is a growing worldwide movement to promote the cultivation of vetiver grass hedgerows as a powerful way of reducing the velocity of rainwater runoff and recharging groundwater. The Vetiver Network, supported by the World Bank, the Government of Denmark and several global NGOs claims that rainwater runoff is reduced by 70 percent when vetiver hedgerows are planted across the slope by slowing down and spreading out runoff over a larger area because the strong roots of this grass can penetrate hard pans and improve infiltration. The Network claims Indian evidence, which shows that where such hedgerows are planted, water levels in wells are higher and springs do not dry up or run longer into the dry seasons (www.vetiver.com).

Domestic Rainwater Harvesting

Groundwater depletion has also revived popular interest in domestic rainwater harvesting techniques, both traditional and new. In water-stressed regions of countries like India, some of these techniques—evolved and used over centuries—are still preserved and in use although in far-flung areas. But these are now coming back into the mainstream in a big way and, in the process, are being improvised upon. *Khadin*s of Rajasthan, *Tanka*s of Western Gujarat, and a whole new range of roof-water-harvesting techniques are coming back into vogue. Since time immemorial, Jordan and its surrounding territories have been replete with honeycombs of family cisterns for rainwater-harvesting and domestic use. These were an inevitable component of a dwelling for centuries but had fallen into disuse with the onset of the modern piped water-supply system. The family cistern is finding its use again (Wahlin 1997). In the city of Rajkot in the water-short Saurashtra region of western India, 1,500 new houses and apartments built during 1997 had incorporated design-changes for rainwater-harvesting and storage found in old houses in the region but forgotten in recent decades (Shah 2000). Baluchistan and parts of Afghanistan have the extraordinary *karezes* which have served both as excellent structures for community water supply and irrigation; these are dying but need to be revived and improvised upon. Some exciting work on bringing back traditional rainwater-harvesting technologies is being done by individuals and small groups in the US. Several variations of this basically involve capturing and storing rainwater in some sort of a tank and using the water with or without treatment. The University of Texas has built a system of three cascading ponds, somewhat like the system tanks of Tamilnadu in South India, to support aquatic life for its biology laboratory fed by harvested rainwater. In the coastal desert of North Chile, a fog collection project has been able to provide an average of 11,000 l/day of water to a community of 330 people (Schemenauer and Cereceda 1991). Many of these ideas may appear before-their-time now; but if water scarcity is to grow at the rate IWMI projects it to (Seckler, Molden, and Barker 1998), their time will surely come, and sooner rather than later.

From Development to Management Mode

Worldwide, then, there is some action by way of a response to the growing scarcity of groundwater; but it is too little, too late, too experimental, too curative, and too supply-side-oriented; there is precious little to reduce demand for groundwater or on approaches to economizing on its use. The only examples we can find of combination of demand- and supply-side-interventions are in the Western US, which has suffered amongst the most-extensive groundwater depletion problems anywhere in the world, and that before anyone else did. In the Santa Clara valley south of San Fransisco bay, overdraft was estimated at

52,000 acre-feet way back in 1949 when India was still on bullock bailers and Persian wheels. The response to sustained overdraft was for new institutions to be created, such as the Santa Clara Water Conservation District and a water user association. Ten dams were constructed to store flood waters for recharge; barriers of injection wells were created to prevent seawater intrusion; arrangements were made to import 100,000 acre-feet of water annually. But, besides these supply-side interventions, there were also measures to restrict the withdrawals through the creation of groundwater zones and the levy of a groundwater tax that varied across zones according to the cost of alternative supplies. As a result, as of the mid-1980s, groundwater table has stabilized at 30 feet above the historic lowest, and land subsidance has become a matter of the past (Coe 1988).

Such examples abound in the Western US; and these provide important pointers to the rest of the world about where to direct ameliorative action. A major problem in transferring these lessons wholesale to developing-country contexts, however, is the numbers involved: in Santa Clara Groundwater District, the total number of farmers was probably less than a thousand; in an area of comparable size, Asia would have over 100,000 farmers. The average stakes per farmer too would vary by a factor of a thousand or more. As a result, spontaneous collective action by groundwater users to protect and manage the resource is far less likely—and more difficult to sustain—in Asia.

Which is perhaps why Asian and other developing-country governments tend to rely more heavily on enacting laws to regulate groundwater use and abuse. However, these are yet to deliver the desired regulation, either in Asia or elsewhere in the developing world. China’s new water law requires that all pumpers get a permit; but the law is yet to be enforced; it is able to extract close to an economic price from canal irrigators; but groundwater is still free. South Africa’s new water law and water policy enshrine the principles of "user pays; polluter pays;" but these are yet to be operationalized. India has been toying around with a draft model groundwater bill for 20 years; but is not able to make it into a Law due to doubts about enforcing such a law on more than 14 million irrigation pumpers scattered through a vast countryside. The establishment of Aquifer Management Councils called COTAS (*Consejos Técnicos de Aguas*) in Mexico, as part of its water reforms, under the new Mexican water law is a notable development; IWMI researchers in Guanjuato are, however, skeptical and hopeful at once: “...several factors bode ill for their (COTAS’) future effectiveness in arresting groundwater depletion. Most importantly, ... their main role will be advisory in nature and they will not have the mandate to resolve conflicts between water users or restrict groundwater extractions. Moreover, there is an unclear division of tasks and responsibilities between COTAS, irrigation water users’ associations, the federal and state water management agencies and the river basin council. On the other hand, the COTAS provide a vehicle for groundwater users to engage in self-governing, collective action and to find innovative solutions to the vexing problem of groundwater depletion.” (Wester, Pimentel, and Scott 1999).

Institutional solutions to sustainable groundwater management that have a chance to work may pose complex issues of equity. Some of these became evident in the tiny World Bank-supported Taiz project in the Habir aquifer of Yemen with the objective to develop a partnership between rural and urban groundwater users, to transfer water from country to town on equitable terms and ensure the sustainability of the resource. The project—which affected a small group of 7,000 rural residents on the Habir aquifer—failed either to transfer water or to ensure its sustainability but suggested important lessons about why it failed. Taking an egalitarian stance, the project tried capacity building of all the 7,000 residents to assume rights over the aquifer and manage the transfer of water to the city; however, the real stakeholders were 22 irrigation pumpers—who used over 90 percent of the aquifer—and not the 7,000 residents. The practicalities of achieving the project aims required that the *de facto* rights of these 22 users were recognized, and incentives were created for *them* to sustainably manage the resource. The pumpers would oppose, frustrate, or sabotage all institutional efforts that infringed their *de facto* rights and failed to provide *them* incentives for sustainable management—which meant that sustainability could be possible only by reinforcing existing inequalities. The report on a World Bank consultation that analyzed the lessons of the Taiz project concluded: "In our judgement, "the egalitarian option" is not viable and ultimately counter productive since it is unlikely to work" (Briscoe 1999,12).

There are potentially powerful *indirect* demand-management strategies that are not even part of the academic discussion in the developing world. These offer important trade-offs that need closer scrutiny. For example, it has been suggested that the Indian Punjab's groundwater depletion problems could be easier to resolve if its export of "virtual" groundwater in the form of rice could be reduced or stopped; on the other hand, IWMI researchers have argued that using rainwater for rice cultivation may be an efficient way of recharging the aquifers, especially because evaporation from rice fields is limited and, after intensive working of soils, paddy fields provide ideal sites for recharge. Water-saving irrigation research—such as for rice in China—can help reduce groundwater use; but it needs to be examined if these technologies would work as well in dry areas. There is also scope and need for more orderly development of groundwater for irrigation, especially in South Asia and West Africa where potential for groundwater development still exists. One approach tried in the Shanxi province of China is of "well-unit" construction. The idea is to undertake overall planning and construction of tube wells on the basis of a hydrogeological zone where the total number of tube wells as well as their siting are determined taking into account the groundwater potential. A well unit typically involves 660 hectares in the plains and 330 hectares in the mountainous regions. The approach has the advantage of scientific construction of wells, unified management and optimal dispatching of water, monitoring and maintenance of equipment and scalar economies in capital costs (FAO 1994). In the Yinhuang irrigation district, conjunctive use of canal water and groundwater has been tried out with some success on a large area of 94,800 hectares (ibid.). Tax-subsidy regimes too have been used to restrict withdrawals. In the overdeveloped Ogalla aquifer in Texas and Oklahoma, which supplies about 30 percent of all groundwater irrigation in the US [4] (www.facingthefuture.org), the rate of over-withdrawal declined partly because of increased cost of pumping and improved application efficiency and partly because of government programs such as the Conservation Reserve Program and Payment-in-Kind Program which offered added incentives to reduce cropping (Llamas, Back, and Margat 1992).

In the business-as-usual scenario, problems of groundwater overexploitation worldwide will only become more acute, widespread, serious and visible in the years to come. The frontline challenge is not just supply-side innovations but putting into operation a range of corrective mechanisms before the problem becomes either insolvable or not worth solving. This involves, what Marcus Moench calls, a transition from the resource "development" to the resource "management" mode (Moench 1995). Even in

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[4] One-fifth, according to Postel (1999).

South Asia—where symptoms of overexploitation are all too clear—groundwater administration still operates in the "development" mode, treating water availability to be unlimited, and directing their energies on enhancing groundwater production. A major barrier that prevents transition from the groundwater *development* to *management* mode is lack of information. Many countries with severe groundwater depletion problems do not have any idea of how much groundwater occurs and who withdraws how much groundwater and where. Indeed, even in European countries where groundwater is important in all uses, there is no systematic monitoring of groundwater occurrence and draft (Hernandez-Mora, Llamas, and Martinez-Cortina 1999). Moreover, compared to reservoirs and canal systems, the amount and quality of application of science and management to national groundwater sectors have been far less primarily because unlike the former, groundwater is in the private, "informal" sector, with public agencies playing only an indirect role.

Gearing up for resource management entails at least four important steps:

1. *Information Systems and Resource Planning:* Most developing countries have only a limited or nonexistent information base on groundwater availability, quality, withdrawal and other variables in a format useful for resource planning. The first step to managing the resource is to understand it through appropriate systems for groundwater monitoring on a regular basis, and incorporating the monitoring data in planning the use of the resource. The next is to undertake systematic and scientific research on the occurrence, use and ways of augmenting and managing the resource.

2. *Demand-Side Management:* The second step is to put in place an effective system for regulating the withdrawals to sustainable levels; such a system may include:
    - registering of users through a permit or license system
    - creating appropriate laws and regulatory mechanisms
    - a system of pricing that aligns the incentives for groundwater use with the goal of sustainability
    - promoting conjunctive use
    - promoting "precision" irrigation and water-saving crop production technologies and approaches

3. *Supply-Side Management:* The third aspect of managing groundwater is augmenting groundwater recharge through:

    - mass-based rainwater-harvesting and groundwater-recharge programs and activities
    - maximizing surface water use for recharge
    - improving incentives for water conservation and artificial recharge

4. *Groundwater Management in the River Basin Context:* Finally, groundwater interventions often tend to be too "local" in their approach. Past and upcoming work in IWMI and elsewhere suggests that like

surface water, groundwater resources too need to be planned and managed for maximum basin-level efficiency. This last is the most important and yet the least thought about and understood, leave alone experimented with. Indeed, one of the rare examples one can find where a systematic effort seems to have been made to understand the hydrology and economics of an entire aquifer is the mountain aquifers underlying the West Bank and Israel that are shared and jointly managed by Israelies and Palastinians (Feitelson and Haddad 1998). Equally instructive for the developing world will be the impact of the entry of big-time corporate players—such as Azurix and the US Filter in the Western US—in the business of using aquifers as inter-year water-storage systems for trading of water. As groundwater becomes scarce and costlier to use in relative terms, many ideas—such as trans-basin movement or surface water systems exclusively for recharge—that in the yesteryears were discarded as infeasible or unattractive will now offer new promise.

In sum, then, groundwater offers us few but precious opportunities for alleviating the misery of the poor; but it poses many—and daunting—challenges of preserving the resource itself. A big part of the answer is massive initiatives to augment groundwater recharge in regions suffering depletion; but, in the ultimate analysis, these cannot work without appropriate demand-side interventions. The water vision of a world that future generations will inherit will have to be the one in which groundwater plays its full developmental, productive and environmental role but in a sustainable manner; and the framework of action to realize this vision will mean eschewing the current free-for-all in groundwater appropriation and use, and promoting a more responsible management of this precious resource that is easy to deplete or ruin—through depletion, salinization and pollution.

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