Climatic Change and Groundwater: India's Opportunities for Mitigation and Adaptation

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Abstract

For millennia, India has been using surface storages and gravity flow to irrigate its crops. During the last 40 years, however, India has witnessed a decline in gravity flow irrigation and the rise of a booming "water-scavenging" irrigation economy through millions of small, private tube wells. For India, groundwater has become at once critical and threatened. Climatic change will act as a force-multiplier; it will enhance the criticality of groundwater for drought-proofing agriculture and simultaneously multiply the threat to the resource. Groundwater pumping with electricity and diesel also accounts for an estimated 16-25 million tonnes of carbon emission, 4-6% of the country's total emission. From the point of view of climatic change, India's groundwater hot spots are western and Peninsular India. These are critical for mitigation of, and adaptation to, climatic change. To achieve both, India needs to make a transition from surface storages to "managed aquifer storage" as the comerstone of its water strategy with proactive demand and supply-side management components. In doing this, India needs to learn intelligently from the experience of countries like Australia and the USA that have long experience in managed aquifer recharge.

Evolution of Indian Irrigation

Irrigation has always been central to life and society in the plains of South Asia, i.e., India, Pakistan, lower Nepal, Bangladesh and Sri Lanka. According to Alfred Deakin, a three-time Australian Prime Minister and an irrigation enthusiast of the early 20th century who toured British India in 1890, the region had 12 million hectares (ha) of irrigated land compared with 3 million ha in the USA, 2 million ha in Egypt, 1.5 million ha in Italy and a few hundred thousand ha each in Ceylon (Sri Lanka, since 1972), France, Spain and Victoria (Australia) (The Age 1891). Although Egypt and Sri Lanka are better known as hydraulic civilizations of yore, a century ago British India was the world's irrigation champion. This is not surprising. In

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a normal year, India receives 4,000 km^3 of rainfall precipitation, large by any standard; but a large part of it falls in eastern India. Moreover, almost all of it is received within 100 hours of torrential downpour, making storage and irrigation critical for the survival of agrarian societies. Considering that parts of India, chiefly the Indo-Gangetic Basin, were densely populated and intensively cultivated more than even 2,000 years ago suggests that water-managed agriculture has been the bedrock of civilization in this part of the world. However, the technology of water-managed agriculture has undergone profound changes over the millennia. Three distinct eras of irrigation evolution can be identified according to the technology used and the institutions it has spawned:

Era of Adaptive Irrigation

From time immemorial to the early 1800s, farming communities adapted their agrarian lives to the hydrology of river basins. There are records of numerous, often gigantic, irrigation systems constructed by kings and managed by specialized bureaucracies. This induced historians like Karl Wittfogel (1957) to famously claim that irrigation drove state-formation in oriental societies like India's; and the administrative requirements of managing large, state-run systems were at the root of the rise of despotic authority in these societies during a period when many countries in Europe had well-entrenched republican institutions. However, the sum total of the evidence suggests that, at least in today's South Asia, farming communities and local overlords, rather than the monolithic state, were key irrigation players in Mughal India and earlier. Diverting and managing monsoonal flood water to support riverine agriculture was the dominant mode in northern India and Pakistan with sandy alluvial aquifers; and using them to fill up countless small reservoirs was the standard procedure in hard-rock parts of Peninsular India (Shah 2008a).

Era of Canal Construction

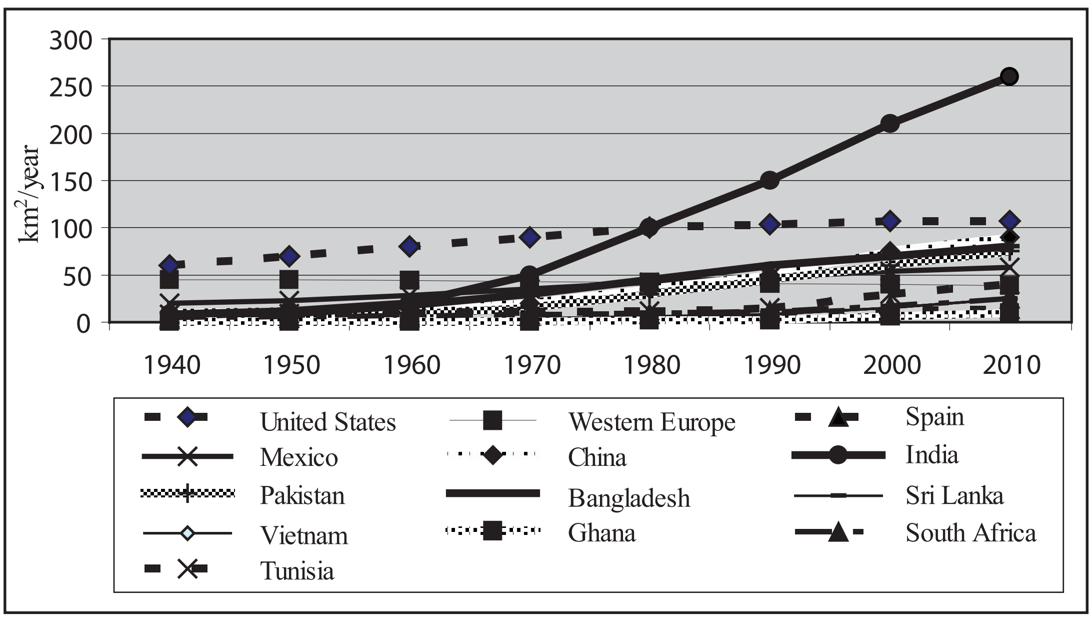
Around 1810, the British East India Company began changing this adaptive irrigation regime by undertaking gigantic projects that reconfigured river basins. The Indus canals transformed northwestern (British) India from a pastoral region to an intensively cultivated terrain. Large canal projects were also undertaken in the south of India. In ambitious irrigation projects, the colonial rulers combined the "interests of charity and the interests of commerce" (Whitcombe 2005). The state and centralized irrigation bureaucracies replaced village communities and local landlords as key players in the new regime. Civil engineering began dominating water planning, construction and management, and continued to do so even after India gained independence and remains predominant today. The colonial era left India and Pakistan with some of the world's largest gravity flow irrigation systems, complete with a highly centralized, bureaucratic irrigation management regime.

Era of Atomistic Irrigation

The colonial irrigation strategy however created pockets of agrarian prosperity in canal commands which even as recently as 2,000 encompassed no more than 15% of India's farming areas. However, India has experienced an explosion in agricultural population since 1960;

and the land:man ratio declined from over 0.4 ha/person in 1900 to less than 0.1 ha/person in 2000. The peasants around the country felt the need to secure a means of irrigation that could permit intensification and diversification of land use. At this time the availability of small mechanical pumps and boring rigs provided a technological breakthrough. Beginning in 1970, this combination of circumstances catalyzed a groundwater revolution all over South Asia. This was a wholly new phenomenon that the water establishment was unfamiliar with. Northwestern India had seen some well-irrigation even during colonial times; however, irrigation of field crops with groundwater was wholly new to humid eastern India and hard-rock Peninsular India. In India, the number of irrigation wells equipped with diesel or electric pumps increased from 150,000 in 1950 to nearly 19 million by 2000. Around 1960, India was a relatively minor user of groundwater in agriculture compared to USA and Spain; by 2000, the country had emerged as the global champion in groundwater irrigation, pumping around 220-230 billion m^3/year, i.e., over twice the amount the USA had pumped as the chart in Figure 1 shows.

Figure 1. Growth in agricultural groundwater use in selected countries during 1940-2010.



Source: Author's estimates based on various sources.

The policy making regarding India's water is yet to fully factor in this epochal transformation in the way its farmers water their crops; and governments keep investing billions of dollars on new surface water reservoirs and canal networks even as the existing ones have begun falling into disuse. Evidence gathered around 2007 suggests that since 1990, central and state governments in India have invested over US$20 billion in building new, and rehabilitating existing, surface irrigation systems; however, the net area served by surface structures, small and large, has actually *declined* by over 3 million ha (Shah 2008a; Thakkar and Chandra 2007). In contrast, net area served by groundwater has been steadily rising. Small farmers looking for opportunities to intensify and diversify their agriculture need year-round on-demand irrigation more frequently. Altough tanks and canal systems are unable to meet this need groundwater wells are able to do so. Groundwater wells are also a better insurance against a drought than tanks and canal systems. As a result, since 1990, Indian irrigation has been transformed from a centrally-managed surface irrigation regime to an atomistically managed water-scavenging irrigation regime involving tens of millions of pump owners who divert surface water and groundwater at will. Even as groundwater irrigation helped South Asia's smallholders survive, myriad environmental impacts have followed as a result of unmanaged overexploitation of the resource. The key consequences of intensification of groundwater use in agriculture in different parts of the subcontinent are given in Table 1.

Table 1. Key consequences of intensification of groundwater use in agriculture in different parts of the subcontinet.

Hydrogeological settings		Socioeconomic and management challenges			
		Resource-depletion	Optimizing conjunctive use	Secondary salinization	Natural groundwater quality concerns
A. Major alluvial plains	A.1. Arid	●●	●●	●●●	●
	A.2. Humid	●	●●●		●●
B. Coastal plains		●●	●	●●●	●
C. Intermontane valleys		●	●●	●	●
D. Hard-rock areas		●●●	●	●	●●●

Note: The number of dots suggests the scale and severity of a challenge.

Groundwater Management Challenges in Different Areas of India

This transformation and the socioecological threats it implied necessitated a totally new policy response from governments and water planners. The meteoric rise of the atomistic groundwater economy demanded bold new thinking and a resource allocation strategy to evolve a groundwater management regime with practical supply- and demand-side strategies. However, steeped in colonial irrigation thinking, Indian water planners still keep spending billions of dollars on the canal irrigation technology that farmers throughout India have been roundly rejecting. If canals are ending up as groundwater recharge structures by default, the question is whether it would not be more effective to do so by design.

Even as India's groundwater irrigation economy remains pretty much ungoverned, climatic change will present new challenges and uncertainties, and demand new responses from the region's water planners. The rise of the booming groundwater economy and the decline in surface irrigation necessitate a totally new understanding of the operating system of India's water economy and how best it can mitigate as well as adapt to the hydro-climatic change.

India's Hydro-Climatic Future

Climatic change is expected to significantly alter India's hydro-climatic regime over the twenty-first century. It is widely agreed that the Indo-Gangetic Basin will experience increased water availability from snowmelt up to around 2030 but face gradual reductions thereafter. Parts of the Indo-Gangetic Basin may also receive less rain than in the past; but the rest of India is likely to benefit from greater precipitation. According to IPCC (2001), most of the Indian land mass below the Ganges Plain is likely to experience a 0.5-1 degree rise in average temperature during 2020-2029 and a 3.5-4.5 degree rise in 2090-2099. Many parts of Peninsular India, especially Western Ghats will experience a 5-10% increase in total precipitation (IPCC 2001);[2] however, this increase will be accompanied by greater temporal variability. Throughout the subcontinent, it is expected that 'very wet days' will contribute more and more to total precipitation suggesting that more of India's precipitation may be received in fewer than 100 hours of hailstorms—and half in less than 30 hours— as has been the case during recent decades. This would mean higher precipitation intensity and a larger number of dry days in a year.[3] Increased frequency of extremely wet rainy seasons (Gosain and Rao 2007) will also mean increased runoff. According to Milly et al. (2008), compared to 1900-1970, most of India will experience a 5-20% increase in annual runoff during 2041-60. All in all, India should expect to receive more of its water through rain than through snow, get used to snowmelt occurring faster and earlier, cope with less soil moisture in summer and higher crop ET demand as a consequence.

For Indian agriculture, hydro-climatic change will mean the following:

- *Kharif* (monsoon from May to September) season crops will experience heightened risk of floods as well as droughts.
- *Rabi* (from October to April) and especially summer crops will experience enhanced ET needing larger, more frequent irrigation.
- Surface water storages—large and small—will benefit from increased runoff but will also suffer increased evaporation from large open surfaces of reservoirs and open canal networks as a result of higher mean temperature.
- Irrigating the same area through canals will necessitate larger reservoir storage; more frequent droughts will also mean greater need for multiyear reservoir storage capacity of which India has very little at present.

[2]In some ways, this may reflect a continuation of some past trends. Based on analyses of rainfall data over the 1872-2005 period, Basishtha et al. (2007) identified a secular decline in rainfall in North India barring Punjab, Haryana, West Rajasthan, Saurashtra and an increase in rainfall in southern India.
[3]By analyzing a daily rainfall data set, Goswami et al. (2006) have shown a rising trend in the frequency of heavy rain events and a significant decrease in the frequency of moderate events over central India from 1951 to 2000.

From these and other points of view, managing groundwater storage will acquire greater significance for India than ever before. However, besides groundwater demand, climatic change is expected to affect groundwater supply too in direct and myriad ways.

Impact of Climatic Change Impacts on Groundwater

To the extent that climatic change results in spatial and temporal changes in precipitation, it will significantly influence natural recharge. Moreover, since a good deal of natural recharge occurs in areas with vegetative cover, such as forests, changing ET rates resulting from rising temperatures may reduce infiltration rates from natural precipitation thus reducing recharge. Recharge responds strongly to the temporal pattern of precipitation as well as to soil cover and soil properties. In the African context, Carter (2007) has argued that replacing natural vegetation by crops can increase natural recharge by up to a factor of 10. If climatic change results in changes in natural vegetation in forests or savanna, these too may influence natural recharge; however, the direction of net effect will depend upon the pattern of changes in the vegetative cover. Simulation models developed by Australian scientists have shown that changes in temperatures and rainfall influence growth rates and leaf size of plants that affect groundwater recharge. The direction of change is conditioned by the context: in some areas, the vegetation response to climatic change would cause the average recharge to decrease, but in other areas, recharge to groundwater would more than double. Changing river flows in response to changing mean precipitation and its variability, rising sea levels, and changing temperatures will all influence natural recharge rates (Kundzewich and Doll 2007).[4]

We know little about how exactly rainfall patterns will change; but increased temporal variability seems guaranteed. This will mean intense and large rainfall events in short monsoons followed by long dry spells. All evidence we have suggests that groundwater recharge through natural infiltration occurs only beyond a threshold level of precipitation; however, it also suggests not only that runoff increases with precipitation but the runoff coefficient (i.e., runoff/precipitation) itself increases with increased rainfall intensity (or precipitation per rainfall event). Higher variability in precipitation may thus negatively impact natural recharge in general. The net impact on a given location will depend upon whether it experiences greater or smaller total precipitation as a result of climatic change.

The Indo-Gangetic aquifer system has been getting heavy recharge from the Himalayan snowmelt. As snowmelt-based runoff increases during the coming decades, their contribution to potential recharge may increase; however, a great deal of this may end up as “rejected recharge” and enhance river flows and intensify the flood proneness of eastern India and Bangladesh. As the snowmelt-based runoff begins declining, one should expect decline in runoff as well as in groundwater recharge in this vast basin.[5]

A major interplay of climatic change and groundwater will be witnessed in coastal areas. Using the records of coastal tide gauges in the north Indian Ocean for more than 40 years, Unnikrishnan and Shankar (2007) have estimated a rise in sea level between 1.06 and 1.75 mm per year, consistent with 1-2 mm per year global sea-level rise estimates of IPCC.

[4] www.gwclim.org/presentations/plenary/kundzewicz.pdf

[5] Data monitored on the Himalayan glaciers present a confusing picture. They indicate recession of some glaciers in recent years, but the trend is not consistent across the entire mountain chain.

Rising sea levels will threaten coastal aquifers. Many of India's coastal aquifers are already experiencing salinity ingress. This problem is particularly acute in the Saurashtra Coast in Gujarat and the Minjur aquifer in Tamil Nadu. In coastal West Bengal, Sundarban is threatened by saline intrusion overland, affecting its aquifers. The precarious balance between freshwater aquifers and seawater will come under growing stress as sea levels rise. According to the Ghyben-Herzberg relation, a 1 foot rise in sea level decreases the depth of the freshwater-seawater interface by 40 times as much (Kundzewich and Doll 2007). Coastal aquifers are thus likely to face serious threats from rise in the sea level induced by climatic change.

Some scientists suggest climatic change may alter physical characteristics of aquifers themselves.[6] Higher CO_2 concentrations in the atmosphere, they argue, may influence carbonate dissolution and promote the formation of crest that, in turn, may negatively affect infiltration properties of the topsoil. Others have argued the opposite. From experimental data, some scientists have claimed that elevated atmospheric CO_2 levels may affect plants, the vadose zone and groundwater in ways that may hasten infiltration from precipitation by up to 119% in the Mediterranean climate and up to 500% in the subtropical climate.[7]

Rethinking Storage

The response of aquifers to droughts and climatic fluctuations is much slower than that to surface storages; as a result, compared to surface storages, aquifers act as a more resilient buffer during dry spells, especially when they have large storages. This is why India has experienced explosive growth in groundwater demand during recent decades; and this is also why groundwater demand will expand further in the wake of climatic change. For millennia, groundwater wells have been the principal weapon Indian farmers have used to cope with droughts (Shah 2008a). This is evident from the fact that digging of wells has tended to peak during drought years. This trend continues even today and will likely increase with heightened hydro-climatic variability. All in all, while we can predict with confidence that climatic change will enhance the demand for groundwater in agricultural and other uses, there is no clarity on whether climatic change will enhance or reduce natural groundwater recharge in net terms under the business-as-usual (BAU) scenario.

For millennia, India has relied on building surface storages and gravity-flow irrigation to water crops. With the groundwater boom, India's irrigation economy has been fundamentally transformed, bringing into question its age-old emphasis on surface structures. Climatic change raises new questions about continued reliance on surface storage and transport of water to agriculture, and demands that India fundamentally rethink its storage strategy. Table 2 compares four storage alternatives India faces along a dozen criteria using a ten-point scale that assigns up to five '↑' signs for positives (benefits) and up to five '↓' signs for the negatives (costs, disbenefits). The four alternatives compared are:

- The first, advocated by environmental and civil society groups, emphasizes numerous small decentralized storages close to the point of use and with short canals. India's age-old

[6]Aquifers are also of interest to researchers on climate for other reasons. Growing literature on Carbon Capture and Storage (CCS) and Geological Sequestration hints at opportunities that aquifers—especially saline and otherwise unusable—offer themselves as "carbon storehouses." This paper, focusing on climatic change-groundwater-agriculture interaction, does not deal with these aspects.

[7]www.sciencedaily.com/releases/2007/10/071006091012.htm

traditional water harvesting structures—such as tanks in South and eastern India, *ahar-pyne* systems of southern Bihar, homestead ponds of West Bengal and North Bihar, *johads* of Rajasthan—represent this class (Choppra 2005).

- The second, emphasized by government bureaucracies, represents the dominant colonial and post-colonial strategy of creating large reservoirs at hydraulically opportune sites and transporting water through a vast network of surface canals.
- The third represents the groundwater boom India has experienced in which mostly shallow aquifer storage has been relentlessly exploited through atomistic action by millions of small farmers without any demand-side management or a systematic strategy of enhancing aquifer recharge.
- The fourth represents an option that is as yet nonexistent but can be operationalized with a paradigmatic shift in the country's water management thinking; it recognizes that groundwater demand will increase, but given India's hydrology, aquifer storage can sustain this increase with proactive demand management and a nationwide program of Managed Aquifer Recharge.

Table 2. Climatic change and water storage alternatives.

		Small surface storages	Large surface reservoirs	Aquifer storage (BAU)	Managed Aquifer storage
1	Makes water available where needed (space utility)	↑↑↑	↑↑	↑↑↑↑	↑↑↑↑↑
2	Makes water available where needed (time utility)	↑	↑↑	↑↑↑↑	↑↑↑↑↑
3	Level of water control offerd (form utility)	↑	↑↑	↑↑↑	↑↑↑↑
4	Non-beneficial evaporation from storage	↓↓↓↓	↓↓	↓	↓
5	Non-beneficial evaporation from transport	↓↓	↓↓↓	↓	↓
6	Protection against mid-monsoonal dry spell (2-8 weeks)	↑↑	↑↑↑	↑↑↑↑↑	↑↑↑↑
7	Protection against a single annual drought	↑	↑	↑↑↑	↑↑↑↑↑
8	Protection against two successive annual drought	↑	↑	↑↑	↑↑↑↑
9	Ease of storge recovery during a good monsoon	↑↑↑↑↑	↑↑↑↑	↑↑	↑↑↑
10	Social capital cost of water storge and transport and retrieval structures	↓↓	↓↓↓↓↓	↓↓	↓↓↓
11	Operation and maintenance of social costs of storage, transport and retrieval structures	↓	↓↓	↓↓↓↓↓	↓↓↓
12	Carbon footprint of agricultural water use	↓	↓↓	↓↓↓↓↓	↓↓↓

Rows 4, 5, 10, 11 and 12 in Table 2 include costs or disadvantages of different storage structures; the rest are benefits/positives. Of the benefits and costs, some, like operating costs (row 11) and quality of access (rows 1, 2 and 3) are private in nature and drive the choices of individual farmers. Others are "public" (or social) in nature; for instance, the carbon-footprint of alternative storage systems may not directly influence individual farmer decisions but they have to be factored into the national calculus.

Since the 1970s, high scores of groundwater irrigation on space, time and form utility (rows 1, 2 and 3) have driven India's groundwater boom. Also important has been the resilience of groundwater against dry spells and droughts (rows 6, 7 and 8). Surface storages have fared poorly on these counts. These benefits will become more valuable as climatic change heightens the hydrological variability. From the society's viewpoint, aquifer storage has the advantage of minimum non-beneficial evaporation (rows 4 and 5); for a mostly semiarid country, where surface reservoirs can lose 3 meters or more of their storage every year simply through pan-evaporation; this is no mean gain. The major social disadvantages of heavy dependence on groundwater are: (a) aquifers are slow to recharge; and hard rock aquifers that underlie 65% of India have limited storage; (b) while gravity flow irrigation from canals needs little or no energy, groundwater irrigation is energy-intensive; and (c) since the bulk of the energy used in pumping groundwater uses diesel or electricity generated with coal, India's transition from flow irrigation to pump irrigation has created a massive carbon footprint.

Carbon Footprint of India's Groundwater Economy

Transformation of Indian irrigation from gravity-flow to lift has made it highly energy-intensive; but the arithmetic of computing the carbon footprint of this economy is fraught with widely divergent estimates. Around 2000, Indian farmers lifted some 150 km^3 of groundwater using electric pump sets and around 80 km^3 using diesel pump sets. Lifting 1,000 m^3 of water to a height of 1 meter uses up 2.73 kWh of energy without friction losses and at peak efficiency (Nelson and Robertson 2008, personal communication). Indian electric irrigation pumps probably operate at 40% efficiency; moreover, transmission and distribution losses in delivering power to pump sets are of the order of 25% or higher. This implies that electricity actually used to lift 1,000 m^3/m in India is of the order of 9.1 kWh. If we assume that a representative electric pump lifts water to a dynamic head of 20 meters, then lifting 150 km^3 of groundwater requires 27.3 billion kWh of electricity. This estimate is highly sensitive to the assumption about the dynamic head over which a representative electric pump set lifts water. Taking a value of 40 meters yields an electricity consumption value of 55 billion kWh.

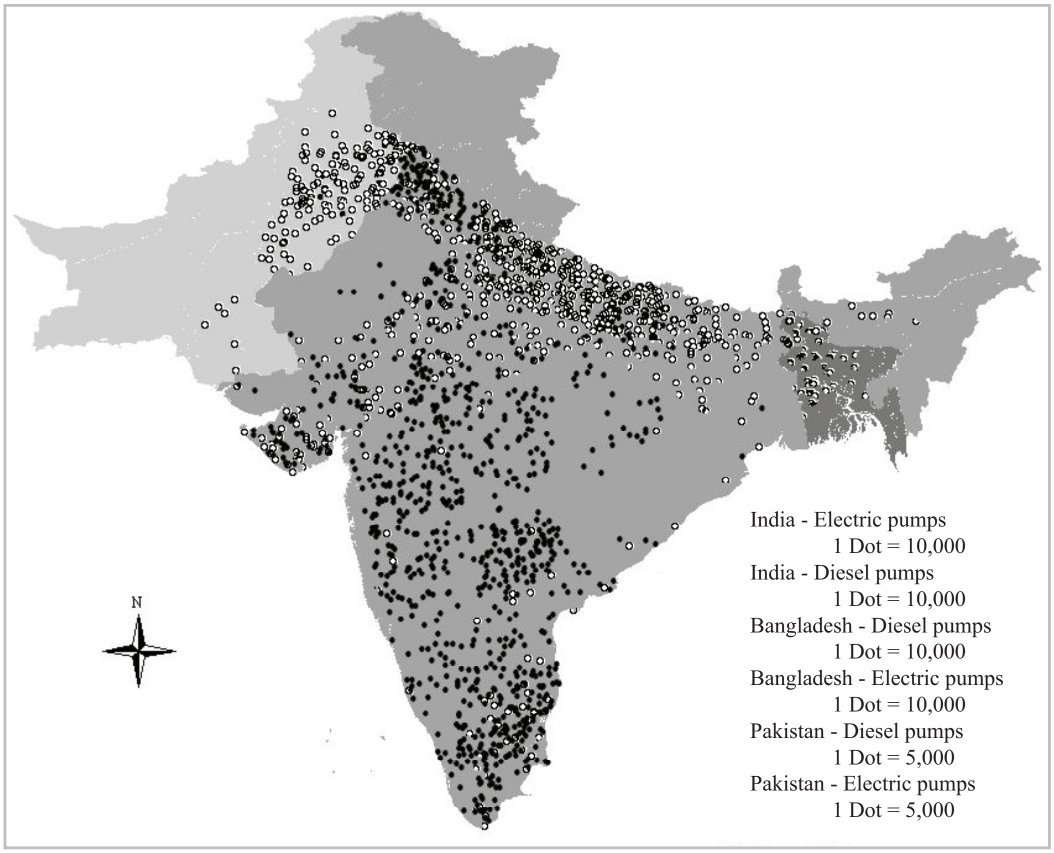
Using India's 2001 Minor Irrigation Census data on groundwater irrigated area[8] and the energy consumed in agriculture (Planning Commission 2007, annexure 2.4)[9] combined with some assumptions, Rao (2008, personal communication) estimated total electricity consumption in groundwater irrigation at 87 billion kWh. Another indirect estimate is provided from numbers circulating in the electricity industry. The total power generation in India is around 560 billion kWh; and many observers suggest that power used by irrigation pumps may be around 15% of the total generation (Planning Commission 2007), giving a total agricultural consumption of around 84 billion kWh. However, this means that either the transmission and

[8] wrmin.nic.in/micensus/mi3census/reports/integrated/integrated_report.htm

[9] planningcommission.nic.in/reports/genrep/rep_grndwat.pdf

distribution (T&D) losses are much higher than 25% as we assumed[10] or that the dynamic head over which a representative electric pump set in India lifts water is more like 50-60 meters rather than 20 meters that our estimate of 27.3 billion kWh is based on. The latter appears highly unlikely; the 2001 Minor Irrigation Census (Government of India 2005a, Table 6.2) found that just around 8.5% of India's villages had a static water level deeper than 50 meters; in 75% of the villages, depth to static water level was less than 15 meters. True, pumping depth can be much higher than the static water level; yet, such a huge difference is difficult to explain.

Figure 2. Distribution of electric and diesel pump sets in South Asia.



Diesel pumps are even less efficient but they lift water to a smaller head; moreover, diesel does not face the T&D losses that electricity suffers and a liter of diesel provides an equivalent of 10 kWh of energy. Some 80 km^3 of groundwater lifted by diesel pump sets uses around 4-4.5 billion liters of diesel. A paper under preparation at the IFPRI has taken the carbon intensity of electricity and diesel at 0.4062 kgC/kWh and 0.732 kgC/liter, respectively (Nelson and Robertson, 2008, personal communication). This would imply that groundwater pumping in India results in the emission of a total of some 14.38 million tonnes of C—11.09 million tonnes by electric pumps and 3.29 million tonnes by diesel pump sets. IFPRI work in progress

[10]A study by Indian Institute of Management, Ahmedabad claims that of the "actual calories used by farmers out of 100 calories generated at the power plant are barely 2%" (IIMA: 93). This excludes the fossil energy used in mining and transporting the fuel for the thermal plants.

tentatively estimates the C-emission from groundwater irrigation to be higher at 16 million tonnes, roughly 4% of India's total C-emissions.

Two interesting aspects of the carbon footprint of India's groundwater economy are that: (a) lifting 1,000 m^3/m using electricity emits 5.5 times more C than using diesel; and diesel pumps are concentrated in eastern India with rich alluvial aquifers; (b) C-emission of groundwater irrigation is highly sensitive to the dynamic head over which groundwater is lifted because, first, higher head leads to higher energy use and C-emission; second, beyond a depth of 10-15 meters, diesel pumps become extremely inefficient forcing irrigators to switch to electricity which has a larger C-footprint anyway. Figure 2 shows that most of India's diesel pumps are concentrated in eastern India and her electric pumps, in western and Peninsular India. Table 4 presents this distribution for all of groundwater-irrigating South Asia, i.e. India, Pakistan, Bangladesh and the Nepal terai region. Indeed, as the calculations made by J. Rao in Table 4 show, 96% of India's electricity use in groundwater pumping is concentrated in 11 states of western and Pzzh eninsular India. Even amongst these, the biggest C-culprits are states like Karnataka, Tamil Nadu, Andhra Pradesh and Gujarat which have large areas under deep tube well irrigation. Deep tube wells have a huge C-footprint; according to preliminary calculations of IFPRI, India's deep tube wells irrigate only 4.1 million ha of the 31 million ha under electric pump set irrigation; but these account for nearly two-thirds of C-emission from groundwater pumping with electric pump sets.

Table 3. Geographic distribution of electric and diesel irrigation pumps in South Asia.

	Number of irrigation pumps (million)	Diesel (%)	Electric (%)
Pakistan	0.93	89.6	10.4
Bangladesh	1.18	96.7	3.3
Eastern India: Assam, West Bengal, Bihar, Orissa, Jharkhand, Uttar Pradesh, Uttarakhand, West Bengal	5.09	84.0	16.0
Western and southern India: Andhra Pradesh, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Punjab, Rajasthan, Tamil Nadu	11.69	19.4	80.6

Sources: 1. Values for Pakistan are from Pakistan Agricultural Machinery Census 2004.
2. Values for Bangladesh are from Mandal 2006.
3. Values for Indian states are from the third Minor Irrigation Census 2000-01 (Government of India 2005a).

Table 4. Estimates of electricity consumption by pump sets in major states of India.

State	Gross area irrigated with electric pumps	Average kWh used per ha of irrigation	Total electricity used by electric pumps (gWh)
Rajasthan	3,844	1,111.8	42,74,000
Uttar Pradesh	14,010	353.4	49,51,000
Haryana	2,267	2,432.1	55,14,000
Madhya Pradesh	2,783	2,006.5	55,83,000
Punjab	5,748	1,086.2	62,43,000
Karnataka	1,285	6,997.0	89,93,000
Tamil Nadu	1,666	5,630.9	93,82,000
Maharashtra	3,311	3,193.0	1,05,72,000
Andhra Pradesh	2,294	5,863.4	1,34,48,000
Gujarat	2,713	5,293.6	1,43,61,000
Others	5,060	7,436.0	37,62,500
Total	44,981	1,934.9	8,70,31,584

Source: Rao, J., personal communication 2008.[11]

An alternative procedure for estimating C-emissions from India's groundwater economy, set out in Table 5, too draws heavily on the data provided by the Minor Irrigation Census. The Census provides numbers of different groundwater and lift irrigation structures, diesel as well as electric pumps, and gross area irrigated by each class. Several micro-level surveys suggest that deep tube wells in India operate for around 1,600 hours/year, that diesel pumps, because of high fuel cost, operate for around 600 hours, but electric pumps, subject to a flat tariff charge operate for 800-1,000 hours. Without having to estimate the energy needed to lift water from different depths, it is assumed that annual hours of operation for different structures are based on survey data. Average horse power ratings of different structures are averaged from the data provided by the Census. The T&D losses in power between generating station and well-head are assumed at 30%. This procedure (a) yields a total C-emission of 25.64 million tonnes from India's lift irrigation economy, some 60% higher than the IFPRI estimate and around 6.4% of India's total emissions; (b) shows deep tube wells to be less "dirty" than the IFPRI procedure makes them out to be; and (c) shows diesel pumps to have a much lower carbon footprint than electric pumps as the IFPRI analysis suggests.

[11]https://login.yahoo.com/config/login_verify2?.intl=us&.src=ygrp&.done=http%3a//groups.yahoo.com%2Fgroup%2FWaterWatch%2Fmessage%2F6680 (last consulted on November 14, 2008).

Table 5. An alternative procedure for estimating C-emission from India's groundwater economy.

	Deep tube wells	Shallow tube wells: electric	Shallow tube wells: diesel	Dug wells: electric	Dug wells: diesel	Surface lift: electric	Surface lift: diesel
Number of structures (m)	0.53	3.26	4.37	6.15	1.99	0.33	0.21
Gross area irrigated (m ha)	4.09	11.61	16.06	9.99	3.23	1.22	0.78
Average horse power	9.66	6.26	6.26	4.43	4.43	5.1	5.1
Energy use/hour at well-head	7.3 kWh	4.7 kWh	1.25 (liters)	3.3 kWh	0.9 (liters)	3.83 (liters)	1
Average hours of operation/ year	1,600	900	600	900	600	600	600
Average hours/ha	207.3	252.8	163.5	554.2	369.6	162.2	162.2
T&D efficiency[12]	70%	70%		70%		70%	
Total energy used[13]	8.34 b kWh	19.7 b kWh	3.28 b	26.1 b kWh	1.07 b	1.1 b kWh	0.13 b
Total estimated emission (tonnes)[14]	3.39	8.0	2.4	10.6	0.78	0.45	0.1
Emission/ha (C-tonnes)	0.83	0.69	0.15	1.06	0.24	0.37	0.13

Discussions on climatic change and groundwater are at a very early stage in India. However, preliminary studies show massive scope for reducing the C-footprint of India's groundwater economy. Using data for Haryana and Andhra Pradesh, Shukla et al. (2003) built a quantitative model to estimate the marginal impacts of a host of factors on greenhouse gas (GHG) emissions from pumping. Some of the conclusions of the study were: (a) every meter decline in pumping water levels increases GHG emissions by 4.37% in Haryana and 6% in Andhra Pradesh; (b) the elasticity of GHG emissions with respect to percent of area under groundwater-irrigation is 2.2; and through the 1990s, groundwater irrigated area in these two states increased at a compound annual growth rate of 3%/year, resulting in an increase in GHG emission at 6.6%/year; (c) every 1% increase in the share of diesel pumps to total pumps reduces GHG emissions by 0.3%; and (d) the elasticity of GHG emissions with respect to irrigation efficiency is high at 2.1. The most important determinant of the C-footprint of India's pump irrigation economy is the dynamic head over which farmers lift water to irrigate crops.

[12] Transmission and distribution efficiency in conveying power between generating station and well-head

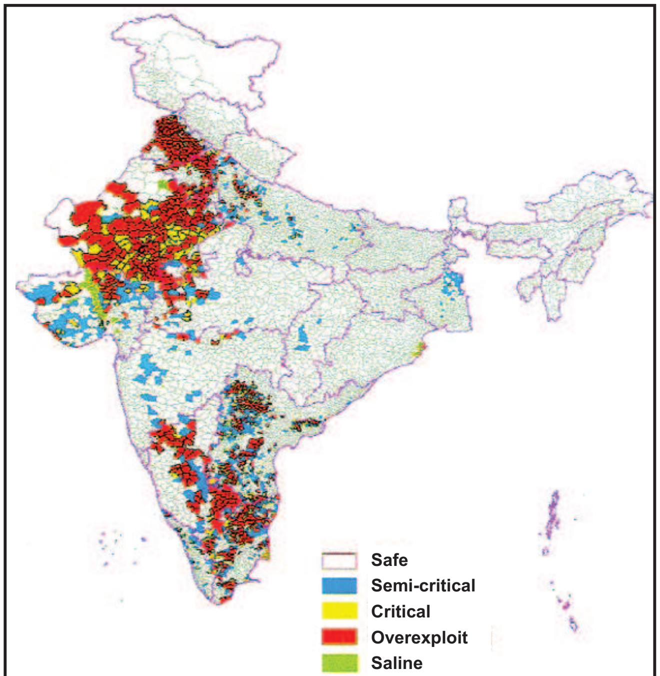
[13] Computed by multiplying rows 5, 4 and 1

[14] C-emission per kWh of electricity is assumed at 0.4062 kg and per liter of diesel at 0.732 kg (Nelson and Robertson 2008).

Groundwater Recharge for Adaptation and Mitigation

From the viewpoint of climatic change, India's groundwater hot spots are concentrated in arid and semiarid areas of western and Peninsular India, especially in Punjab, Rajasthan, Maharashtra, Karnataka, Gujarat, Andhra Pradesh and Tamil Nadu, as is evident from the map of groundwater overexploited areas (Figure 3). Continued overexploitation of groundwater has severely curtailed the resilience of their aquifers and their ability to stabilize farming livelihoods in the face of heightened hydro-climatic variability. Groundwater here is pumped from great and increasing depths mostly using coal-based electricity; hence, these are also the regions which account for an overwhelmingly large proportion of GHG emissions from groundwater pumping. Accepting the present dependence of agriculture on groundwater as a fait accompli should lead policymakers to evolve a strategy of "proactive management of aquifer storage" as the central plank of India's water strategy in the years to come. This strategy needs to incorporate effective means to manage agricultural water demand as well as to enhance natural groundwater recharge through large-scale "Managed Aquifer Recharge" investments. Without demand- and supply-side management of the pump irrigation economies, groundwater levels in most Indian aquifers display behavior caricatured in Figure 4a. In the initial years, water level fluctuations before and after the monsoon get amplified; however, as pre-monsoonal water levels drop considerably below the vadose zone, natural recharge rates decline and the pumping head increases rapidly. With proactive demand and supply-side management, the situation desired is caricatured in Figure 4b. With groundwater development, fluctuations will amplify; however, as long as post-monsoonal water levels bounce back to predevelopment levels with managed aquifer recharge, a steady state can be approached, albeit with rising average pumping head.

Figure 3. Groundwater-stressed areas of India.



Source: Planning Commission, 2007.

Figure 4a. Groundwater development and water level decline without managed aquifer recharge.

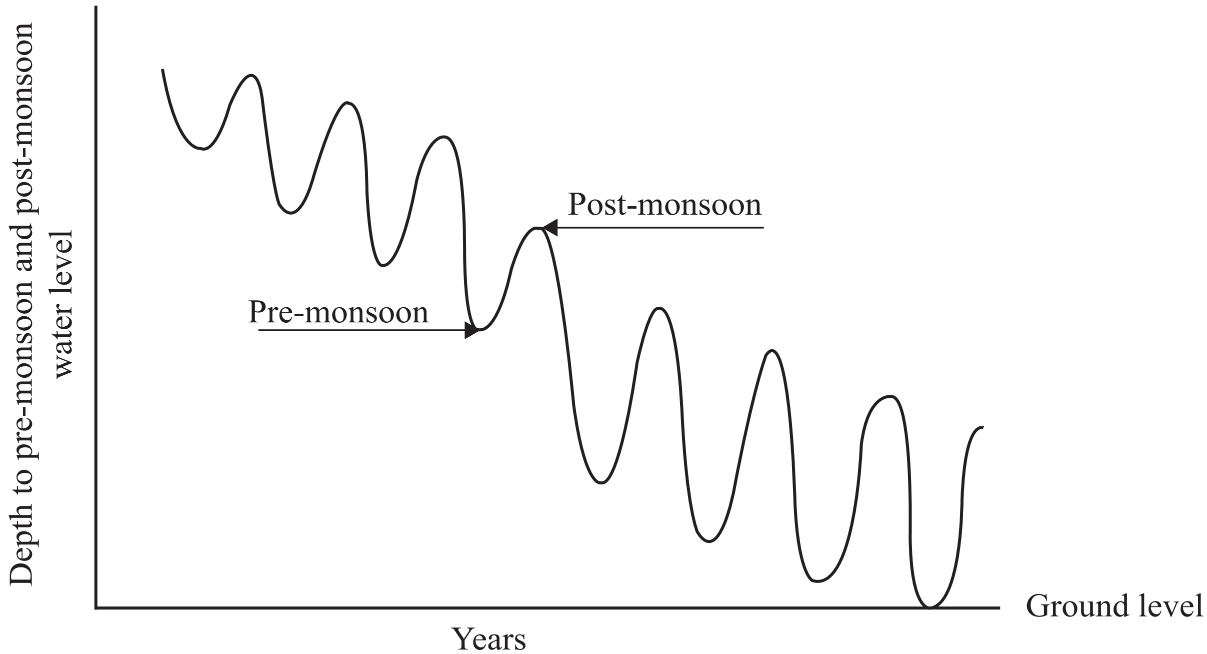
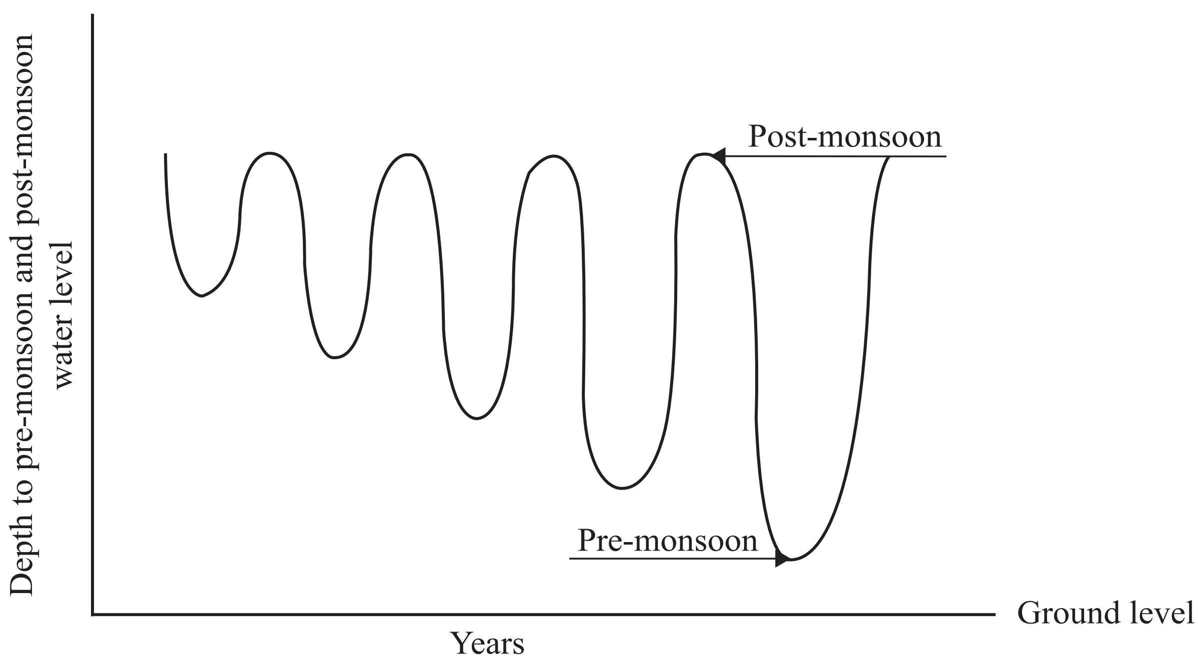


Figure 4b. Groundwater development and water-level behavior with intensive program of managed aquifer recharge.



India has witnessed growing discussions on how best to manage the runaway expansion in demand for agricultural groundwater. Laws and administrative regulations-such as licensing-have been extensively discussed and even tried; however, the key challenge is in enforcing these on several tens of millions of widely dispersed pumpers in a vast countryside (Planning Commission 2007). Many observers have also suggested pricing of groundwater but the administrative and logistical challenges of doing these are even more formidable. Groundwater irrigation is the mainstay of India's small farmers and the rural poor; therefore, governments and political leaders are reluctant to adopt a heavy-handed approach to curtail groundwater demand (Shah 2008b). The political objective therefore is to seek environmental goals in ways that do not hit the poor. For over a decade, IWMI has argued that, in the short run, the only effective and practical approach of groundwater demand management in India is through rationing of agricultural power supply (Shah et al. 2004). During recent years, Gujarat in western India has experimented with this approach with considerable success. The government of this state invested US-$ 250 million in rewiring rural Gujarat's electricity infrastructure under *Jyotirgram* scheme to separate feeders supplying power to farm-consumers from those that take power to nonfarm rural consumers. The electricity company has been rationing farm power supply, forcing farmers to use power and groundwater more efficiently, and curtailing aggregate groundwater withdrawals significantly (Shah et al. 2008).

On the supply side, the key transition India needs to make is from surface-storage to aquifer storage. Intensive groundwater development has created problems, but also opportunities. Until the 1960s, when India withdrew 10-20 km^3 of groundwater, it experienced very little natural recharge to its predevelopment aquifer-storage; most runoff was rejected recharge. Today, India's Central Groundwater Board estimates that some 10% of India's annual precipitation of 4,000 km^3 ends up as natural recharge without any significant effort on anybody's part. If a fraction of the resources and energies that India expends on building new surface reservoirs and canal systems is directed to promoting large-scale groundwater recharge in her groundwater hot spot areas of western and Peninsular India, the country can greatly reduce its GHG emissions from pumping and also restore the resilience of its aquifers to protect agriculture from heightened hydro-climatic variability (Shah 2008b).

Groundwater recharge therefore needs to become the new mantra for India's water policy. In this respect too, India needs to evolve strategies and technologies that suit its unique conditions. In hard-rock areas of India, farmers have built over 9 million large open wells at their own cost. These can be up to 8 meters in diameter and 60-70 meters in depth. Many have also invested in several—sometimes dozens of—horizontal and vertical bores inside them to enhance their connectivity with nearby water-bearing fractures. So far, these wells are used only for withdrawing water; but these can as well be used as excellent recharge structures if the sediment-load of surplus flood-water during monsoons could be reduced using simple filtering and desilting technologies. However, Indian thinking on groundwater recharge is shaped by the experiences and technologies used in the western USA and Australia; as a result, government hydrogeologists tend to prefer large spreading type recharge structures to working with millions of well owners to modify their wells for recharge. India needs to use the vast technological experience of Australia and the USA to design recharge programs but in a manner that incorporates its unique features. While there is no substitute for large spreading-type recharge structures in recharging large confined aquifers, not using millions of farmer-owned open wells for recharge is a great opportunity lost (Shah 2008b).

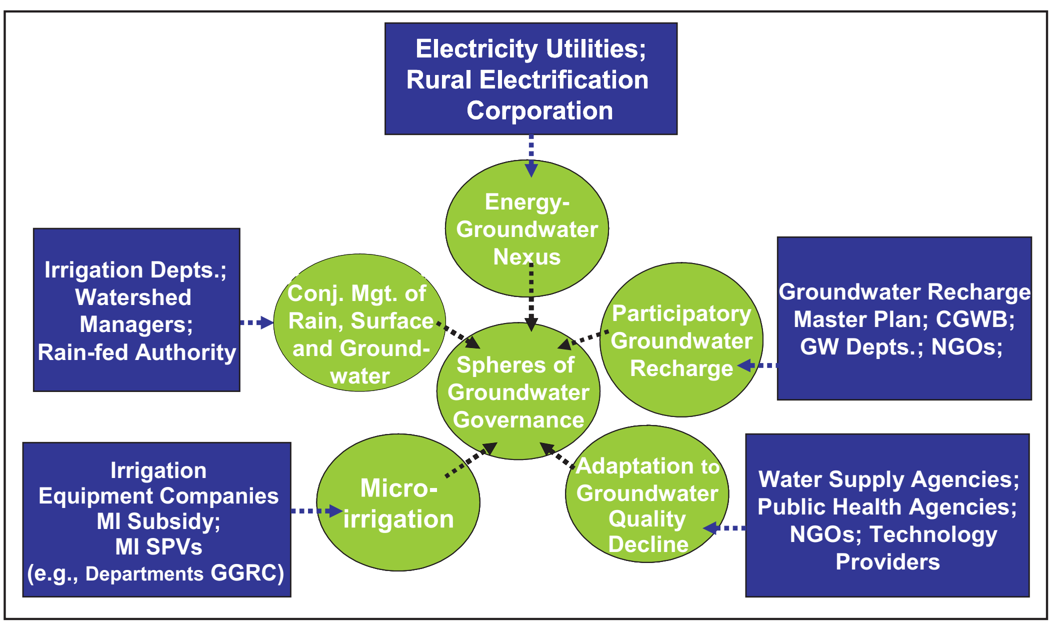
Conclusion: Need for a Paradigm Change

In 2001, India's Central Groundwater Board produced a Master Plan for Groundwater Recharge (Government of India 2005b). While the plan had many limitations and flaws, its most striking contribution was its objective of stabilizing static post-monsoonal groundwater level throughout India at 3 meters below the ground through a national program of groundwater recharge. Pursuing such a bold objective can be India's best feasible response to mitigating climatic change as well as adaptation. However, doing this entails a major rethink by India of its water policy and administration.

Reorienting India's water strategy to meet the challenge of hydro-climatic change demands a paradigm change in the official thinking about water management. Although the groundwater agencies of the government are the custodians of our groundwater resource, in reality, multiple agencies in public and private sectors are major players in India's groundwater economy**.** As climatic change transforms groundwater into a more critical and yet threatened resource, there is dire need for coordinating mechanisms to bring these agencies under an umbrella framework to synergize their roles and actions. Even as governments evolve groundwater regulations and their enforcement mechanisms, more practical strategies for groundwater governance need to be evolved in five spheres as outlined in Figure 5 (Shah 2008a). Synergizing the working of agencies in these spheres offers the best chance to bring a modicum of order and method to the region's water-scavenging irrigation economy.

As of now, managing the energy-irrigation nexus with sensitivity and intelligence is India's principal tool for the management of groundwater demand. Gujarat's experiment has already been mentioned earlier; but other ideas need to be tried, given that energy-irrigation nexus holds the key to minimizing C-footprint of Indian irrigation. There has been a debate on the value of aggressively promoting micro-irrigation technologies. Some experts have argued that micro-irrigation technologies, such as drip irrigation, save water that would have otherwise

Figure 5. India's groundwater governance pentagram.



Notes: Depts. = Departments. SVPs = Special Purpose Vehicles. CGWB = Central Ground Water Board. GGRC = Gujarat Green Revolution Co.

returned to the aquifer for later use. However, in the context of climatic change, micro-irrigation is important for energy savings even more than water savings. Indeed, in the context of climatic change, water management structures and strategies need to achieve joint maximization of water productivity as well as energy efficiency.

In hard-rock India, together with intelligent management of the energy-irrigation nexus, mass-based decentralized groundwater recharge offers a major short-run supply-side opportunity. Public agencies are likely to attract maximum farmer participation in any program that augments on-demand water availability around farming areas. Experience also shows that engaging in groundwater recharge is often the first step for communities to evolve norms for local, community-based demand management.

In alluvial aquifer areas, conjunctive management of rain, surface water and groundwater is the big hitherto underexploited opportunity for supply-side management. Massive investments being planned for rehabilitating, modernizing and extending gravity-flow irrigation from large and small reservoirs need a major rethink in India. In view of the threat of climatic change, India needs to rethink our storage technology itself. Over the past 40 years, India's land mass has been turned into a huge underground reservoir, more productive, efficient and valuable to farmers than surface reservoirs. For millennia, it could capture and store little rainwater because in its predevelopment phase it had little unused storage. The pump irrigation revolution has created 230-250 km^3 of new, more efficient storage in the subcontinent. Like surface reservoirs, aquifer storage is good in some places and not so good in others. To the farmers, this reservoir is more valuable than surface reservoirs because they have direct access to it and can obtain water on demand. Therefore, they are far more likely to collaborate in managing this reservoir if it responds to their recharge pull (Shah 2008 forthcoming).

In mainstream irrigation thinking, groundwater recharge is viewed as a by-product of flow irrigation, but in today's India, this equation needs rethinking. Increasingly, the country's 250 odd km^3 of surface storage make economic sense only for sustaining on-demand groundwater irrigation in extended command areas. A cubic meter of recharged well water, available on demand, is valued many times more than a cubic meter of water in surface storage. Farmers' new-found interest in local water bodies throughout semiarid Peninsular India reflects the value of groundwater recharge. This is evident in South Indian tank communities that are converting irrigation tanks into percolation tanks, and in Saurashtra and Kutch, where a new norm intended to maximize groundwater recharge forbids irrigation from small surface reservoirs so that recharge gets maximized.

In some areas of India with massive evaporation losses from reservoirs and canals but with high rates of infiltration and percolation, the big hope for surface irrigation systems—small and large—may be to reinvent them to enhance and stabilize groundwater aquifers that offer water supply close to points of use, permitting frequent and flexible just-in-time irrigation of diverse crops. Already, many canal irrigation systems create value not through flow irrigation but by supporting well irrigation by default through farmers investing in tube wells in command areas. But canal systems need to be redesigned for maximizing recharge over a larger area than the command. While farmers are doing their bit, the management of the system itself tends to be totally antithetical to optimal system-wide conjunctive use (Shah 1993). Management of surface systems is clearly in dire need of reinvention.

Surface systems in water-stressed regions of western India need to be remodeled to mimic the on-demand nature of groundwater irrigation. In Rajasthan's Indira Gandhi Canal, the government is subsidizing farmers to make farm ponds, to be filled by the canal once a month and then used to supply water on demand. Gujarat is following suit through a new program of supporting farmers in command areas to build on-farm storage from which they can irrigate on demand. Integrating large canal irrigation projects in the groundwater irrigation economy may support the case for rethinking their modernization in ways previously unimagined. Replacing lined canals with buried perforated pipes connected to irrigation wells or farm and village ponds, thus creating recharge paths along the way, may be a more efficient way of using surface storage than flow irrigation.

There is a new groundswell of enthusiasm for pipes rather than for open channels to transport water. The use of pipes for water transport is also valued for at least two other benefits: first, saving scarce farmland otherwise used for watercourses and field channels, and second, micro-irrigation. In the Sardar-Sarovar Project in Gujarat the major water user associations refused to build water distribution systems because of land scarcity. In an agrarian economy with already high population pressure on farmland, flexible pipes for water distribution make more sense than surface channels, and buried pipes are even better. Pipes also support micro-irrigation technologies. This is what explains a boom in the use of plastics in many parts of Indian agriculture. And if China's experience is any guide, this boom will continue to generate water as well as energy savings.

By far the most critical response to hydro-climatic change in India's water sector demands exploring synergies from a variety of players for a nationwide groundwater recharge program. Evolving a groundwater recharge strategy appropriate to India needs to begin with an appreciation of the variety of actors that can contribute through different kinds of recharge structures as suggested in the following table. Public agencies with strong science and engineering capabilities need to play a major role in constructing and managing large recharge structures. However in India, an intelligent strategy can also involve millions of farmers and householders—and thousands of their communities—each of whom can contribute small volumes to recharge dynamic groundwater. When we approach the problem thus, new strategic avenues present themselves. India's water policy has so far tended to focus on what governments and government agencies can do. Now, it needs to target networks of players, each with distinct capabilities and limitations. If groundwater recharge is to be a major response to hydro-climatic change, the country needs to evolve and work with an integrated groundwater recharge strategy with roles and space for various players to contribute.

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