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# Climate change and groundwater: India's opportunities for mitigation and adaptation

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**Abstract**

For millennia, India used surface storage and gravity flow to water 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 tubewells. For India, groundwater has become at once critical and threatened. Climate change will act as a force multiplier; it will enhance groundwater's criticality 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 mt of carbon emissions, 4–6% of India's total. From a climate change point of view, India's groundwater hotspots are western and peninsular India. These are critical for climate change mitigation as well as adaptation. To achieve both, India needs to make a transition from surface storage to 'managed aquifer storage' as the center pin 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 United States that have long experience in managed aquifer recharge.

**Keywords:** climate change, groundwater, irrigation, adaptation, India

## 1. Evolution of Indian irrigation

Irrigation has always been central to life and society in the plains of South Asia—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 United States, 2 million ha in Egypt, 1.5 million ha in Italy and a few hundred thousand ha each in Ceylon, 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 a normal year, India receives 4000 km$^3$ of rainfall precipitation, large by any standards; but a large part of it falls in eastern India. Moreover, almost all of it is received within 100 h 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 even before 2000 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 spawned:

*Era of adaptive irrigation.* Since time immemorial until 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 Wittfogel (1957) to famously claim that irrigation drove state formation in oriental societies like

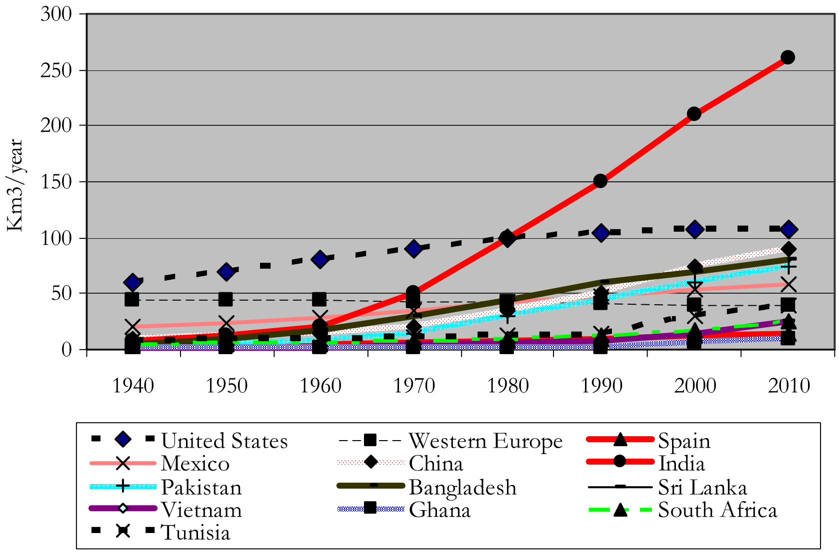

**Figure 1.** Growth in agricultural groundwater use in selected countries: 1940–2010. Source: Shah *et al* (2007).

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 monsoon floodwaters to support riverine agriculture was the dominant mode in northern India and Pakistan with sandy alluvial aquifers where harvesting and storing rainwater in unlined surface tanks and reservoirs was subject to high seepage losses. In contrast, using monsoon floodwaters to fill up countless small reservoirs was the standard procedure in hard-rock parts of peninsular India where seepage losses from water storages were insignificant (Shah 2009).

*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 north-western (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, 677). 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 became independent 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 (i.e. the area below the reservoir/weir irrigated by gravity canals) which even as recently as in 2000 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 need was felt by peasants around the country to secure the means of irrigation which could permit intensification and diversification of land use. 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. North-western 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 some 150 000 in 1950 to nearly 19 million by 2000. Around 1960, India was a relatively minor user of groundwater in agriculture compared to countries like the United States and Spain; by 2000, the country had emerged as the global champion in groundwater irrigation, pumping around 220–230 billion m$^3$ year$^{-1}$, over twice the amount the US did, as the chart in figure 1 shows.

India's water policy making 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 reservoirs and canal networks even as the existing ones have begun falling into disuse. Evidence around 2007 suggests that, since 1990, central and state governments in India have invested over US $20 billion on 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 2009, Thakkar and Chandra 2007). In contrast, the net area served by groundwater has been steadily rising. Small farmers looking for opportunities to intensify and diversify their agriculture need year-round irrigation on-demand with

**Table 1.** Groundwater management challenges in different areas of India. (Note: the number of dots suggests the scale and severity of a challenge (1 dot = minor, 2 dots = significant, 3 dots = severe).)

| | | Socio-economic and management challenges | | | |
|---|---|---|---|---|---|
| Hydro-geological settings | | 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 Inter-montane valleys | | ● | ●● | ● | ● |
| D. Hard-rock areas | | ● ● ● | ● | ● | ● ● ● |

great frequency. Tanks and canal systems are unable to meet this need; but groundwater wells are. 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 and groundwater at will. Even as groundwater irrigation helped South Asia's smallholders survive, myriad environmental impacts have followed as a result of unmanaged over-exploitation of the resource. Table 1 outlines the key consequences of intensification of groundwater use in agriculture in different parts of the sub-continent.

This transformation, and the socio-ecological 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 resource allocation strategy to evolving 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, climate 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 decline in surface irrigation necessitates 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.

## 2. India's hydro-climatic future

Climate change is expected to significantly alter India's hydro-climatic regime over the 21st century. It is widely agreed that the Indo-Gangetic basin is likely to experience increased water availability from snow-melt 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 Indian landmass below the Ganges plain is likely to experience a 0.5–1 °C rise in average temperatures during 2020–2029 and 3.5–4.5 °C rise in 2090–2099. Many parts of peninsular India, especially the Western Ghats, are likely to experience a 5–10% increase in total precipitation (IPCC 2001)[1]; however, this increase is likely to be accompanied by greater temporal variability. Throughout the sub-continent, it is expected that 'very wet days' are likely to contribute more and more to total precipitation, suggesting that more of India's precipitation may be received in fewer than 100 h of thunderstorms—and half in less than 30 h—as has been the case during recent decades. This is likely to mean higher precipitation intensity and larger number of dry days in a year[2]. Increased frequency of extremely wet rainy seasons (Gosain and Rao 2007) is also likely to mean increased run-off. According to Milly *et al* (2008), compared to 1900–1970, most of India is likely to experience 5–20% increase in annual run-off during 2041–60. All in all, India should expect to receive more of its water through rain than through snow; get used to snow-melt occurring faster and earlier; and cope with less soil moisture in summer and higher crop evapotranspiration (ET) demand as a consequence.

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

- Kharif (monsoon) season crops will experience heightened risk of flood as well as droughts.
- Rabi and especially summer crops will experience enhanced ET, needing larger, more frequent irrigation.
- Surface water storages—large and small—will benefit from increased run-off 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 multi-year reservoir storage capacity, of which India has very little as of now.

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

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[1] In some ways, this trend may reflect a continuation of some past trends. Based on analyses of rainfall data over the 1872–2005 period, Basishtha *et al* (2007) identified secular decline in rainfall in North India barring Punjab, Haryana, West Rajasthan and Saurashtra and increase in rainfall in southern India.

[2] Goswami *et al* (2006) by analyzing a daily rainfall dataset 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.

## 3. Climate change impacts on groundwater

To the extent that climate 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 and thus reduce recharge. Recharge responds strongly to temporal pattern of precipitation as well as 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 climate change results in changes in natural vegetation in forests or savanna, these too may influence natural recharge; however, the direction of the net effect will depend upon the pattern of changes in the vegetative cover. Simulation models developed by Australian scientists have showed that changes in temperatures and rainfall influence growth rates and leaf size of plants that affect groundwater recharge (Kundzewicz and Doll 2007). The direction of change is conditioned by the context: in some areas, the vegetation response to climate 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 (Kundzewicz and Doll 2007)[3].

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 run-off increases with precipitation but the run-off coefficient (i.e. run-off/precipitation) itself increases with increased rainfall intensity (or precipitation per rainfall event) (Carter 2007). Higher variability in precipitation may thus negatively impact natural recharge in general. What will be the net impact on a given location will depend upon the change in both the total precipitation and the variability of that precipitation.

The Indo-Gangetic aquifer system has been getting heavy recharge from the Himalayan snow-melt. As snow-melt-based run-off 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 snow-melt-based run-off begins declining, one should expect a decline in run-off as well as groundwater recharge in this vast basin[4].

A major interplay of climate 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 sea level rise between 1.06 and 1.75 mm per year, consistent with the 1–2 mm per year global sea level rise estimates of IPCC. Rising sea levels will threaten coastal aquifers. Many of India’s coastal aquifers are already experiencing salinity ingress. This problem is particularly acute in Saurashtra coast in Gujarat and Minjur aquifer in Tamil Nadu. In coastal West Bengal, Sundarbans (mangrove forest) are threatened by saline intrusion overland, affecting its aquifers. The precarious balance between freshwater aquifers and sea water will come under growing stress as sea levels rise. Coastal aquifers are thus likely to face serious threats from climate-change-induced sea level rise.

Some scientists suggest climate change may alter the physical characteristics of aquifers themselves[5]. Higher $CO_2$ concentrations in the atmosphere, they argue, may influence carbonate dissolution and promote the formation of carst which in turn may negatively affect infiltration properties of topsoils. Others have argued the opposite. From experimental data, some scientists have claimed that elevated atmospheric $CO_2$ levels may affect plants, vadose zone and groundwater in ways that may hasten infiltration from precipitation by up to 119% in a Mediterranean climate to up to 500% in a sub-tropical climate[6].

## 4. Rethinking storage

Aquifers respond to droughts and climate fluctuations much more slowly than surface storages; as a result, compared to surface storages, aquifers act as a more resilient buffer during dry spells, especially when they have large storage. This is the reason 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 climate change. For millennia, groundwater wells have been the principal weapon Indian farmers have used to cope with droughts (Shah 2009). This is evident in the fact that well digging has tended to peak during years of droughts. This trend continues even today and will likely increase with heightened hydro-climatic variability. All in all, while we can predict with confidence that climate change will enhance the demand for groundwater in agricultural and other uses, there is no clarity on whether climate 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. Climate 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

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[3] http://www.gwclim.org/presentations/plenary/kundzewicz.pdf.

[4] Monitoring data on 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 (Singh and Arora 2007).

[5] Aquifers are also of interest to climate researchers 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 as ‘carbon storehouses’. This paper, focusing on climate change–groundwater–agriculture interaction, does not deal with these aspects.

[6] http://www.sciencedaily.com/releases/2007/10/071006091012.htm.

**Table 2.** Climate 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 when needed (time utility) | ↑ | ↑↑ | ↑↑↑↑ | ↑↑↑↑↑ |
| 3 | Level of water control offered (form utility) | ↑ | ↑↑ | ↑↑↑↑ | ↑↑↑↑↑ |
| 4 | Non-beneficial evaporation from storage | ↓↓↓↓ | ↓↓ | ↓ | ↓ |
| 5 | Non-beneficial evaporation from transport | ↓↓ | ↓↓↓ | ↓ | ↓ |
| 6 | Protection against mid-monsoon dry spell (2–8 weeks) | ↑↑ | ↑↑↑ | ↑↑↑↑↑ | ↑↑↑↑↑ |
| 7 | Protection against a single annual drought | ↑ | ↑ | ↑↑↑ | ↑↑↑↑↑ |
| 8 | Protection against two successive annual droughts | ↑ | ↑ | ↑↑ | ↑↑↑↑ |
| 9 | Ease of storage recovery during a good monsoon | ↑↑↑↑↑ | ↑↑↑↑ | ↑↑ | ↑↑↑ |
| 10 | Social capital cost of water storage and transport and retrieval structures | ↓↓ | ↓↓↓↓↓ | ↓↓ | ↓↓↓ |
| 11 | Operation and maintenance social costs of storage, transport and retrieval structures | ↓ | ↓↓ | ↓↓↓↓↓ | ↓↓↓ |
| 12 | Carbon footprint of agricultural water use | ↓ | ↓↓ | ↓↓↓↓↓ | ↓↓↓ |

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 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 (see 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 non-existent 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.

Rows 4, 5, 10, 11 and 12 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 has to be factored into the national calculus.

Especially since the 1970s, the 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 groundwater’s resilience against dry spells and drought (rows 6, 7 and 8). Surface storages have fared poorly on these counts. These benefits will become more valuable as climate 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 semi-arid country, where surface reservoirs can lose 3 m 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 three: (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.

**Table 3.** Geographic distribution of electric and diesel irrigation pumps in South Asia. (Note: Sources: (1) Pakistan figures are from Pakistan Agricultural Machinery Census 2004. (2) Bangladesh figures are from Mandal 2006. (3) Figures for Indian states are from the third Minor Irrigation Census 2000–01.)

| | 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, Jharkhand, Orissa, Uttar Pradesh, Uttaranchal, 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 |

**Table 4.** Estimates of electricity consumption by pumpsets in major states of India.

| States | Gross area irrigated with electric pumps | Average kWh used per ha of irrigation | Total electricity used by electric pumps (GWh) |
|---|---|---|---|
| Rajasthan | 3844 | 1111.8 | 4274 000 |
| Uttar Pradesh | 14 010 | 353.4 | 4951 000 |
| Haryana | 2267 | 2432.1 | 5514 000 |
| Madhya Pradesh | 2783 | 2006.5 | 5583 000 |
| Punjab | 5748 | 1086.2 | 6243 000 |
| Karnataka | 1285 | 6997.0 | 8993 000 |
| Tamil Nadu | 1666 | 5630.9 | 9382 000 |
| Maharashtra | 3311 | 3193.0 | 10 572 000 |
| Andhra Pradesh | 2294 | 5863.4 | 13 448 000 |
| Gujarat | 2713 | 5293.6 | 14 361 000 |
| Other states | 5060 | 7436.0 | 3762 500 |
| Total | 44 981 | 1934.9 | 87 031 584 |
| Source: J Rao 2008[a] | | | |

[a] 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).

## 5. 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 by widely divergent estimates. Around 2000, Indian farmers lifted some 150 km$^3$ of groundwater using electric pumpsets and around 80 km$^3$, using diesel pumpsets. Lifting 1000 m$^3$ of water to a height of 1 m uses up 2.73 kWh of energy without friction losses and at peak efficiency (Nelson and Robertson 2008). Indian electric irrigation pumps probably operate at 40% efficiency; moreover, transmission and distribution losses in delivering power to pumpsets are of the order of 25% or higher. This implies that the electricity actually used to lift 1000 m$^3$ m$^{-1}$ 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 m, 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 pumpset lifts water. Taking a figure of 40 m yields an electricity consumption figure of 55 billion kWh. This estimate compares well with the estimate made by the more detailed International Food Policy Research Institute, as set out in table 5 (at 54.50 billion kWh), but smaller than those made by J Rao at 87 billion kWh, as shown in table 4.

Using India's 2001 Minor Irrigation Census data on groundwater irrigated area[7] and the energy consumed in agriculture from (Planning Commission (India) 2007: annex 2.4)[8] combined with some assumptions, Rao (2008) estimated total electricity consumption in groundwater irrigation at 87 billion kWh. Another indirect estimate is provided from the numbers circulating in the electricity industry. 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 (see Planning Commission (India) 2007), giving total agricultural consumption of around 84 billion kWh. However, this means that either the transmission and distribution (T&D) losses are much higher than 25% as we assumed[9] or that the dynamic head over which a representative electric pumpset in India lifts water is more like 50–60 m rather than 20 m that our estimate of 27.3 billion kWh is based on. The latter appears highly unlikely; the 2001 Minor Irrigation Census (Govt of India 2005a, table 6.2) found that just around 8.5% of India's villages had static water levels deeper than 50 m; in 75% of the villages, depth to static water level was less than 15 m. True, pumping depth can be much higher than static water level; yet, such a huge difference is difficult to explain.

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 the equivalent of 10 kWh of energy. Some 80 km$^3$ of groundwater lifted by diesel pumpsets 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$^{-1}$ and 0.732 kgC l$^{-1}$, respectively (Nelson and Robertson 2008). This would imply that groundwater pumping in India results in emission of a total of some 14.38 million mt of C—11.09 million mt by electric pumps and 3.29 million mt by diesel pumpsets. The IFPRI work in progress tentatively estimates the C emission from groundwater irrigation higher at 16 million mt, roughly 4% of India's total C emissions.

Two interesting aspects of the carbon footprint of India's groundwater economy are that: (a) lifting a 1000 m$^3$ m$^{-1}$ 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

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[7] http://wrmin.nic.in/micensus/mi3census/reports/integrated/integrated_report.htm.

[8] http://planningcommission.nic.in/reports/genrep/rep_grndwat.pdf.

[9] 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 is barely 2%' (IIMA, p 93). This excludes the fossil energy used in mining and transporting the fuel for the thermal plants.

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

| | | Deep tubewells | Shallow tubewells: electric | Shallow tubewells: diesel | Dugwells: electric | Dugwells: diesel | Surface lift: electric | Surface lift: diesel |
|---|---|---|---|---|---|---|---|---|
| 1 | Number of structures (m) | 0.53 | 3.26 | 4.37 | 6.15 | 1.99 | 0.33 | 0.21 |
| 2 | Gross area irrigated (m ha) | 4.09 | 11.61 | 16.06 | 9.99 | 3.23 | 1.22 | 0.78 |
| 3 | Av. horse power | 9.66 | 6.26 | 6.26 | 4.43 | 4.43 | 5.1 | 5.1 |
| 4 | Energy use/hour at well-head | 7.3 kWh | 4.7 kWh | 1.25 l | 3.3 kWh | 0.9 l | 3.83 | 1 |
| 5 | Average hours of operation/year | 1600 | 900 | 600 | 900 | 600 | 600 | 600 |
| 6 | Average hours/ha | 207.3 | 252.8 | 163.5 | 554.2 | 369.6 | 162.2 | 162.2 |
| 7 | T&D efficency[a] | 70% | 70% | | 70% | | 70% | |
| 8 | Total energy used[b] | 8.34 b kWh | 19.7 b kWh | 3.28 b l | 26.1 b kWh | 1.07 b l | 1.1 b kWh | 0.13 b l |
| 9 | Total estimated emission (met)[c] | 3.39 | 8.0 | 2.4 | 10.6 | 0.78 | 0.45 | 0.1 |
| 10 | Emission/ha (C-mt) | 0.83 | 0.69 | 0.15 | 1.06 | 0.24 | 0.37 | 0.13 |

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

[b] Computed by multiplying rows 5, 4 and 1.

[c] 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).

highly sensitive to the dynamic head over which groundwater is lifted because, for one, a higher head leads to higher energy use and C emission; and second, beyond a depth of 10–15 m, 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 3 presents this distribution for all of groundwater-irrigating South Asia—that is, India, Pakistan, Bangladesh and Nepal Terai (densely cultivated farming areas, grasslands and forests at the base of the Himalaya range in India, Nepal and Bhutan). Indeed, as the calculations made by Rao in table 4 show, 96% of India's electricity use in groundwater pumping is concentrated in 11 states of western and peninsular India. Even amongst these, the biggest C culprits are states like Karnataka, Tamil Nadu, Andhra Pradesh and Gujarat which have large areas under deep tubewell irrigation. Deep tubewells have a huge C footprint; according to the IFPRI preliminary calculations, India's deep tubewells irrigate only 4.1 million of the 31 million ha under electric pumpset irrigation, but these account for nearly 2/3rd of C emission from groundwater pumping with electric pumpsets.

An alternative procedure for estimating C emissions from India's groundwater economy, set out in table 5, also 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 tubewells in India operate for around 1600 h year$^{-1}$, that diesel pumps, because of high fuel cost, operate for around 600 h, but electric pumps, subject to a flat tariff charge, operate for 800–1000 h. Without having to estimate the energy needed to lift water from different depths, I have assumed annual hours of operation for different structures based on survey data. Average horsepower ratings of different structures are averaged from the data provided by the Census. 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 mt 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 tubewells to be more GHG-emitting 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.

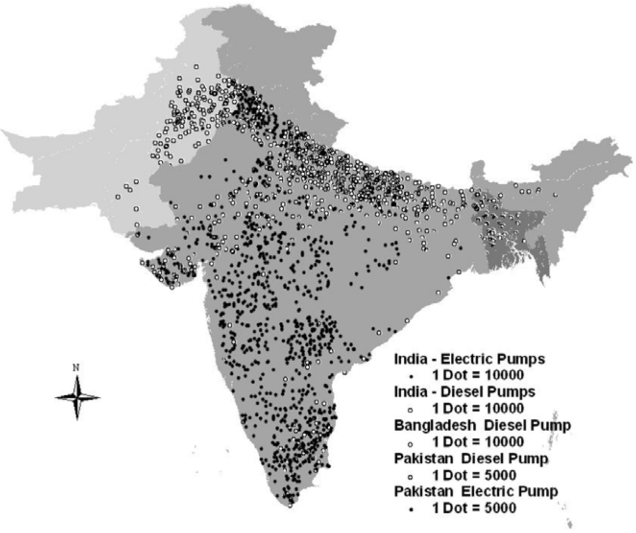

**Figure 2.** Distribution of electric and diesel pumpsets in South Asia.

Climate change and groundwater discussions are at a very early stage in India. However, preliminary studies show massive scope for reducing the C footprint[10] 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 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 w.r.t per cent of area under groundwater irrigation (that is, the per cent increase in GHG induced by a 1% increase in groundwater irrigated area) is 2.2; and through the 1990s, groundwater irrigated area in these two states increased at a compound

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[10] C footprint in the context can be viewed as the volume of GHG released per hectare of groundwater irrigated area.

annual growth rate of 3% $\text{year}^{-1}$, resulting in an increase in GHG emission at 6.6% $\text{year}^{-1}$; (c) every 1% increase in the share of diesel pumps to total pumps reduces GHG emissions by 0.3%; (d) the elasticity of GHG emissions w.r.t 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. The larger the head, the higher the energy consumption and the more likely that electrified deep tubewells are used for pumping groundwater, multiplying the C footprint of groundwater pumping.

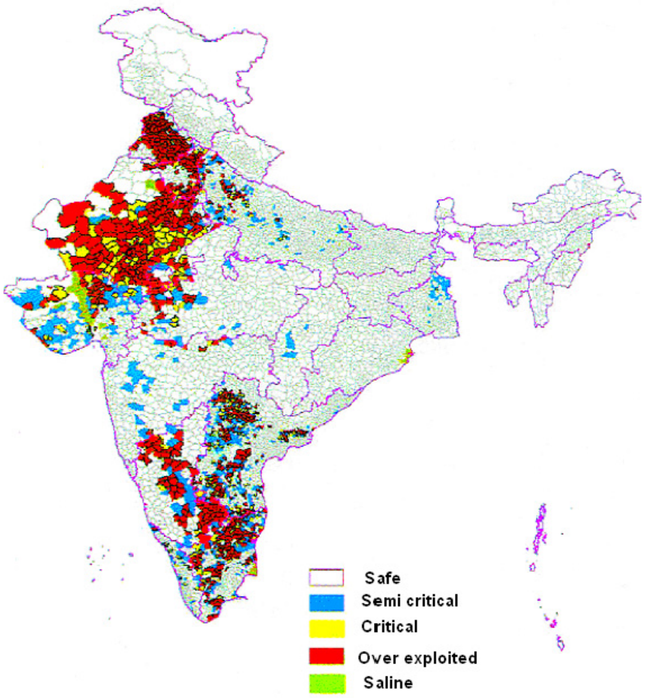

**Figure 3.** Groundwater-stressed areas of India. Source: Planning Commission (India) (2007).

## 6. Groundwater recharge for adaptation and mitigation

From the climate change viewpoint, India's groundwater hotspots are concentrated in arid and semi-arid areas of western and peninsular India, especially in the seven states of Punjab, Rajasthan, Maharashtra, Karnataka, Gujarat, Andhra Pradesh, and Tamil Nadu, as is evident from the map of groundwater over-exploited areas (figure 3). Continued over-exploitation 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 groundwater dependence of agriculture as a fait accompli should lead policy makers 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 characterized in figure 4(a). In the initial years, water level fluctuations before and after monsoon get amplified; however, as pre-monsoon 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 characterized in figure 4(b). With groundwater development, fluctuations will amplify; however, as long as post-monsoon water levels bounce back to pre-development levels with managed aquifer recharge, a steady state can be approached, albeit with rising average pumping head. There is considerable evidence to show that nature itself helps aquifer recovery during monsoons. India's Minor Irrigation Census compiles data on pre-monsoon and post-monsoon water levels in wells from over 500 000 villages. Figure 4(c) plots this data aggregated for 145 districts and arranged in ascending order of pre-monsoon water level. Without significant efforts to enhance natural recharge, this data suggests that monsoonal recovery of water levels tends to increase with pre-monsoon depth to the water level except at very high levels of the latter. Survey data from some 250 villages around the Indian sub-continent around 2002 also suggested a similar positive relationship between pre-monsoon water level and monsoonal rise in water level (Shah *et al* 2006). This suggests that, in the absence of groundwater development, much of the floodwater from rain runs-off as rejected recharge, and that to some considerable extent, post-monsoon groundwater extraction helps to increase natural recharge. An aggressive, nationwide Managed Aquifer Recharge program can enhance natural recharge rates to bring them closer to groundwater utilization rates on an annual basis.

India has witnessed growing discussions on how best to manage the runaway expansion in demand for agricultural groundwater and for the energy needed to pump it. 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 (India) 2007). Many observers have also suggested pricing of groundwater but the administrative and logistical challenges of doing this are even more formidable. Groundwater irrigation is the mainstay of India's small farmers and rural poor; therefore, governments and political leaders are reluctant to adopt a heavy-handed approach to curtail groundwater demand (Shah 2009). The political objective therefore is to seek environmental goals in ways that do not hit the poor. IWMI has argued for over a decade that, in the short run, the only effective and practical approach for 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

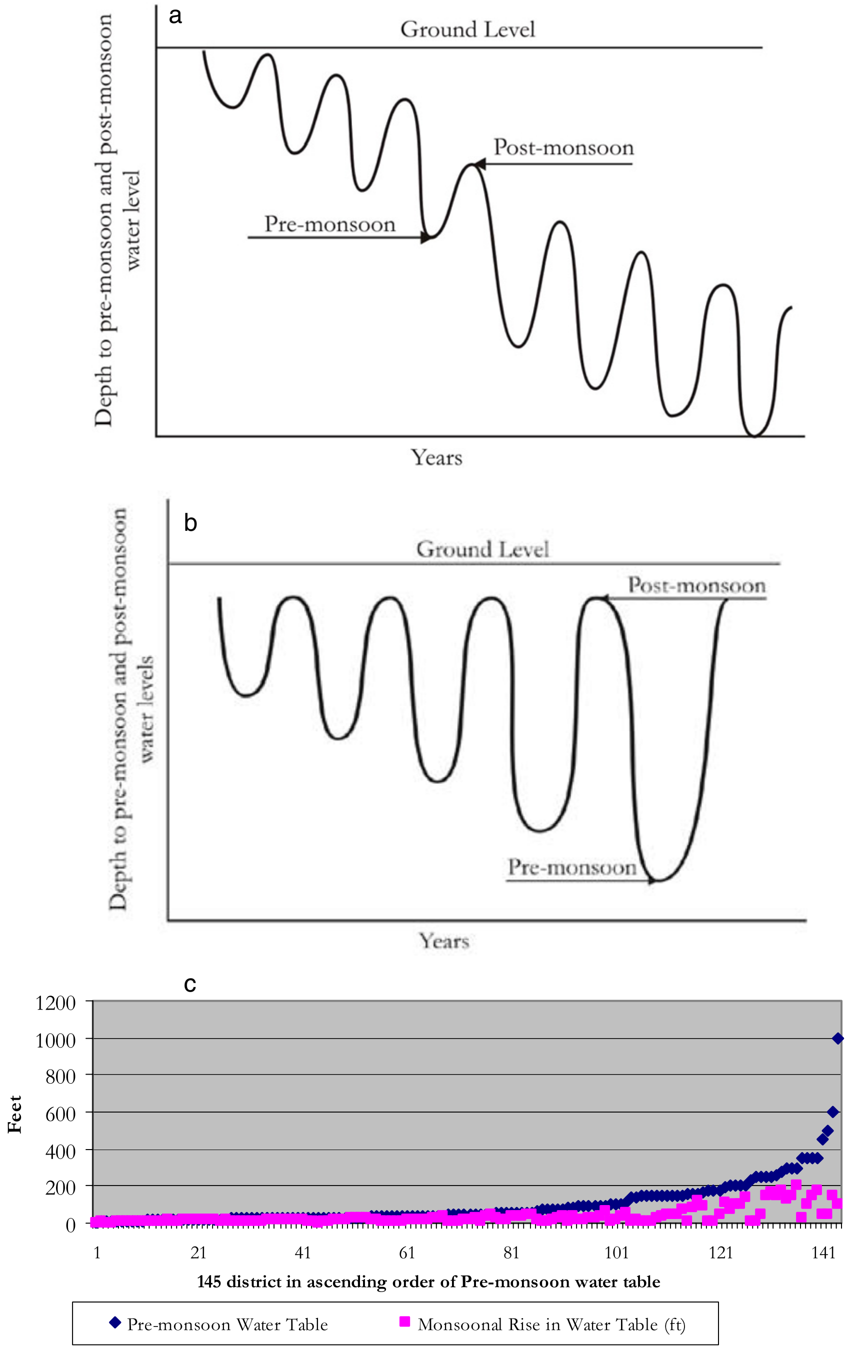

**Figure 4.** (a) Groundwater development and water level decline without managed aquifer recharge. (b) Groundwater development and water level behavior with an intensive program of managed aquifer recharge. (c) Aquifer recovery and pre-monsoon water level in 145 districts of India: minor irrigation census 1993–94.

state invested US $250 million in rewiring rural Gujarat's electricity infrastructure under the *Jyotirgram* scheme[11] to separate feeders supplying power to farm consumers from those that take power to non-farm rural consumers. This done, 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). States which are weighed

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[11] This scheme was a 'second-best' answer to the challenge of controlling subsidies on farm power supply. The first-best solution advocated was to install meters on each tubewell and charge farmers based on their actual power consumption. However, groundwater irrigators in many states have organized to oppose such a move over recent years. The next-best option was to ration power supply to farmers for a fixed number of hours every day. But this could not be done effectively when the same feeder lines provided power to farmers as well as other rural users such as households, cottage industries, hospitals, schools, etc. In a clever move, Gujarat invested US $250 million in rewiring rural Gujarat. By separating feeders supplying power to farmers from those supplying other rural users, Gujarat is now able to effectively impose a power ration on farmers, forcing them to use their electricity ration more efficiently. For a study of the impacts of this scheme, see Shah *et al* (2008).

under a heavy burden of farm power subsidy—such as Gujarat, Rajasthan, Maharashtra, Tamil Nadu and Andhra Pradesh—also aggressively promote drip irrigation technologies among farmers not so much to save water but to save energy. Numerous field studies show that the use of drip irrigation reduces quantity of groundwater pumped per hectare by 30–70%, depending upon the crop and the season. In many other states, farmers use expensive energy to pump groundwater but then lose much of it in evaporation and seepage by conveying it in earthen field channels. Promoting piped conveyance here can save a great deal of energy.

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. As mentioned elsewhere, it is unique to India that farmers in command areas of many canal irrigation systems depend on pumping groundwater for irrigation. Punjab is an excellent example; it has India's largest and best canal network; yet 75% of Punjab's irrigated areas depend upon tubewells for irrigation (Shah 2009). Conjunctive management of surface and groundwater offers large opportunities for improving water productivity as well as saving energy. Conjunctive management can aim at minimizing, throughout the command, average pumping depth of groundwater by spreading water over the command area. This would involve modifying the protocol for main system management as illustrated for the Mahi command area in Gujarat in Shah (1993).

Outside canal commands, the challenge is bigger. Until the 1960s, when India used to withdraw 10–20 km$^3$ of groundwater, it experienced very little natural recharge to its pre-development aquifer storage; most run-off was rejected recharge. Today, India's Central Groundwater Board estimates that some 10% of India's annual precipitation of 4000 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 hotspot areas of western and peninsular India, the country can not only greatly reduce its GHG emissions from pumping but also restore the resilience of its aquifers to protect agriculture from heightened hydro-climatic variability (Shah 2008).

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 m in diameter and 60–70 m 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 floodwaters during monsoons could be reduced using simple filtering and desilting technologies. True, with dugwell recharge, there are threats of groundwater contamination and these need to be contained by intensive campaigns to enhance farmer knowledge about improving the quality of input water as far as practical[12]. However, Indian thinking on groundwater recharge is shaped by the experiences and technologies used in the western United States and Australia; as a result, government hydro-geologists tend to prefer large spreading type recharge structures rather than working with millions of well owners to modify their wells for recharge. India needs to use the vast technological experience of Australia and the US 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 2008).

## 7. Conclusion: need for a paradigm change

In 2001, India's Central Groundwater Board produced a Master Plan for Groundwater Recharge (Govt of India 2005b). While the Plan had many limitations and flaws, its most striking contribution was its objective: of stabilizing static post-monsoon groundwater level throughout India at 3 m below the ground through a national program of groundwater recharge. Pursuing such a bold objective could be India's best feasible response to climate change mitigation as well as adaptation. However, doing this requires that India does a major rethink 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 climate 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 2009). 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 groundwater demand management. Gujarat's experiment was already mentioned earlier, but other ideas need to be tried, given that the energy–irrigation nexus holds the key to minimizing the C footprint of Indian irrigation. There has

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[12] Many western countries permit groundwater recharge only after ensuring that input water is brought to drinking water quality level. In developing countries like India, this may become practical but only in the long run. In any case, fertilizer and pesticide use in much of India is a small fraction of the levels common in western countries; as a consequence, the chemical contaminant load of monsoon run-off is likely to be much smaller than in the west. Moreover, in many parts of India, geogenic contaminants—fluoride, arsenic, etc—are more of a public health hazard; and experience shows that the concentration of these, especially fluoride, declines where vigorous groundwater recharge programs are undertaken.

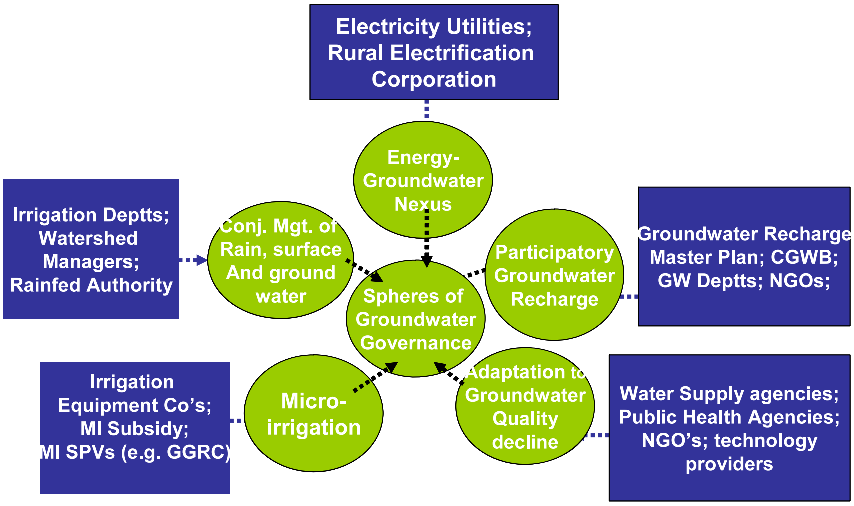

**Figure 5.** India's groundwater governance pentagram.

been a debate on the value of aggressively promoting micro-irrigation technologies. Some experts have argued that micro-irrigation technologies—such as drip irrigation—saves water that would have otherwise returned to the aquifer for later use (Shah and Keller 2002, Narayanamoorthy 2004, Kumar 2003). However, in the climate change context, micro-irrigation is important for energy savings even more than water savings. Indeed, in the context of climate 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 programs that augment 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 climate change, India needs to rethink its storage technology itself. Over the past 40 years, India's landmass 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 pre-development phase it had little unused storage. The pump irrigation revolution has created 230–250 km$^3$ of new, more efficient storage in the sub-continent. Like surface reservoirs, aquifer storage is good in some places and not so good in others. To the farmer, this reservoir is more valuable than surface reservoirs because he has direct access to it and can obtain water on demand. Therefore, he is far more likely to collaborate in managing this reservoir if it responds to his recharge pull (Shah 2009).

In mainstream irrigation thinking, groundwater recharge is viewed as a by-product of flow irrigation, but in today's India, this equation needs to be stood on its head. Increasingly, the country's 250 odd km$^3$ of surface storage makes 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 semi-arid 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 (Shah and Desai 2002).

In areas of India with massive evaporation losses from reservoirs and canals but 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 tubewells 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 systemwide conjunctive use (Shah 1993, pp 176–201). Surface system management 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 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 that connect with irrigation wells or farm and village ponds, 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 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, western India, the major reason water user associations refused to build water distribution systems was 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 (Shah *et al* 2004), 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 Shah (2008). 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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