CHAPTER 16

Socio-ecology of groundwater irrigation in India

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ABSTRACT: Groundwater is the backbone of irrigated agriculture in India. Consequent upon the advent of Green Revolution in India, the use of groundwater has become very intensive. Despite negligible public investment in groundwater irrigation, this source of water contributes more to agricultural wealth and well being than any other source of irrigation. Groundwater irrigation in India is a function more of demand for timely and reliable irrigation in area with high population densities and vibrant agricultural economies, than a function of supply side variables such as availability of groundwater. This has given rise to unsustainable pattern of groundwater use in many parts of the country, where extraction of groundwater has exceeded annual renewable recharge. Groundwater is a so-called *democratic resource* in the sense that individual farmers have direct access to it. Three problems dominate in groundwater scenario in India: depletion, salinization and pollution and these have far-reaching socio-economic and environmental consequences. This pathology of groundwater decline in region after region reflects a remarkably similar 4-stage pattern; from a stage where underutilized groundwater resource becomes instrumental in unleashing agrarian boom to one in which, unable to apply brakes in time, the region goes overboard in exploiting its groundwater resources. This paper examines the trends in groundwater use in India over the decades and offers a first tentative test of the hypothesis that the contribution of groundwater to agricultural wealth creation has risen faster than the contribution from any other irrigation source. In other words, groundwater contributes more to agricultural well being and rural wealth than any other irrigation source *per se.*

1 INTRODUCTION

Groundwater is a significant source of irrigation in India and accounts for more than half of net irrigated area in the country. As per one estimate (Dains & Pawar 1987), 70%–80% of the value of irrigated production in India may depend on groundwater irrigation. This means that a large proportion of India's agricultural Gross Domestic Product (GDP) actually depends on groundwater. According to the World Bank & Government of India (1998) estimates, the contribution of groundwater to India's GDP is around 9%. The great significance of groundwater in the agrarian economy of India is explained by the fact that agricultural yields are generally high in areas irrigated with groundwater than in areas irrigated from other sources (Dhawan 1995). While at an intuitive plane, most researchers agree that groundwater irrigation is more productive than surface water irrigation and there is a lot of field level evidence to support this hypothesis; there is a little hard macro level evidence for the same. The importance of groundwater as a source of productivity and livelihood gains can hardly be over-emphasized. The pattern of groundwater development in India has however, created a number of sustainability, equity and efficiency concerns. Groundwater exploitation levels are alarming in some of the agriculturally developed states of India such as Punjab, Haryana and Tamil Nadu. The development of groundwater resource has been primarily through private initiative of the farmers. Thus, India's groundwater economy actually comprises of more than 19 million groundwater structures spread through the length and breadth of the country, having developed sporadically, rather than through concerted government policies as in the case of canal irrigation (Narain 1998). However, it must be said that indirect government incentives in the form of rural electrification, electricity subsidy policy and credit policies helped in rapid expansion of groundwater irrigation in the country.

This paper offers a tentative macro level empirical test of the proposition that groundwater irrigation may contribute more to Indian agricultural production and growth than even surface irrigation development. The paper uses cross sectional district level data of India for the decades of 1970s (1970–73) and 1990s (1990–93) to ascertain the importance of groundwater irrigation to agricultural production in India. It also examines the factors that play an important role in fostering groundwater development in the country. More specifically, the objectives of this paper are three folds:

a) To understand the dynamics of groundwater use in agriculture.
b) To test the hypothesis that the contribution of groundwater irrigation to agricultural production has risen faster than surface irrigation systems, because groundwater irrigation is more productive and it has grown faster compared to other forms of irrigation. In other words, groundwater contributes more to rural wealth creation than any other source of irrigation.
c) To spell out the factors that encourage and stimulate groundwater use and development in India.

Accordingly, this paper has been divided into eight sections. Sections 1, 2 & 3 deal with introduction, data and coverage, and methodology respectively. Section 4 gives relevant background information on India with special reference to the groundwater situation in the country. Section 5 documents the increasing importance of groundwater irrigation in India; Section 6 presents and tests the hypothesis that groundwater irrigation creates more wealth than any other source of irrigation, while Section 7 delineates the factors that determine groundwater use in India. Section 8 sums up the discussion and throws in a word of caution about the possible socio-ecological fallout of excessive groundwater development.

2 DATA AND COVERAGE

Data from various sources have been used for this study. The source of data and the way the variables are measured in different sources need some elaboration and clarification. The following are the main sources of data:

a) Bhalla & Singh (2001) provide data for value of 35 agricultural crops at 1990 (in Indian Rupees –Rs–, which has been converted to US$ according to 1990 Rs: US$ exchange rate) base year price for four decades –1960s to 1990s. These 35 crops cover more than 90% of the crop output and area cultivated in India. We have worked out productivity figures by dividing the value of these 35 crops (in US$) by the net-cropped area in the district. Bhalla & Singh (2001) data span across 273 districts (1960s base), and include all states except Himachal Pradesh and North Eastern states.
b) ICRISAT-SEPP (1994) data, which they have in turn compiled from Annual Agricultural Statistics Reports of Government of India (GOI). It provides data on source wise irrigated area (i.e. area irrigated by different irrigation systems like canal, tanks, wells, etc. in a district) from 1970–71 to 1993–94 for 12 semi arid tropical states of India. The data exclude Kerala, Himachal Pradesh, North Eastern states and Jammu and Kashmir. There are no data for West Bengal because source wise irrigation data have not been published for the whole of 1990s. These data cover 266 districts (1970s base).
c) CGWB (1995) provides data on all aspects of renewable groundwater resource covering some 396 districts except districts of North East India as well as Assam.
d) GOI's (1986) Minor Irrigation (MI) Census provides data on various aspects of well ownership and distribution for 362 districts in all major states except Kerala, Rajasthan and the North Eastern states.

In our analysis, we have used data from diverse sources. The number of districts covered using Bhalla & Singh (2001) data is 251 (1960s base).

Major states that have been covered are: Andhra Pradesh, Bihar (including Jharkhand), Gujarat, Haryana, Karnataka, Madhya Pradesh (including Chattisgarh), Maharashtra, Orissa, Punjab, Rajasthan and Uttar Pradesh (excluding hilly districts, now Uttaranchal). Another set of data (from CGWB, MI and ICRISAT) is used to analyze the determinants of groundwater use in India covering 225 districts (1960s base) which encompasses all the states mentioned above, with the exception of Rajasthan for which pump density data are not available from Minor Irrigation Census of 1986. The study states cover 81% of geographical area of India and are home to some 82% of India's population. In a broad sense, we have covered all the major Indian states in our analysis whenever requisite data for the same were available.

3 METHODOLOGY

This paper is based on analysis of secondary level district data for all the major Indian states for the period 1970–73 and 1990–93. Methodology used can be divided into two parts. The first involves classification and tabulation of districts into various irrigation categories based on proportion of surface water- and groundwater-irrigated areas to net-cropped area. Similarly, districts have been classified on the basis of groundwater use (groundwater-irrigated area as percentage of net cropped area) and groundwater available for irrigation in net terms. The second involves a series of regression equation models that have been used in Sections 6 and 7 to test our hypotheses. Our first model (reported in Section 6) tries to test the hypothesis that the contribution of groundwater to India's agricultural economy has risen faster than the contribution from any other source of irrigation. This means that groundwater contributed significantly more to total agricultural output in 1990–93, than in 1970–73. In order to test this hypothesis, we ran OLS regression separately for 1970–73 and 1990–93. To further consolidate and strengthen our argument, we pooled together the data for the two decades and using dummy variable for the two periods (1970–73 = 0; 1990–93 = 1), ran another regression with the same independent variables. The results are presented in Section 6. Our second hypothesis tries to establish the fact that demand for groundwater (expressed in terms of population density, past agricultural productivity or agricultural dynamism in a region and agricultural credit off take) is the most important determinant of groundwater use. This is opposed to the popularly held view that groundwater use is governed by supply parameters, both absence of rainfall and surface source of irrigation and presence of abundant groundwater. Here too, we estimated the relative importance of demand and supply variables in two separate equations and then pooled all the variables together to find out the importance of all the variables in determining groundwater use. Due to obvious data constraints, we could only test this hypothesis for a single time period, i.e. for the early 1990s (roughly the period of 1990–95). We used the 1990 (averaged for 12 months) Rs:US$ exchange rate to convert the agricultural productivity and credit data expressed in Rs/ha to US$/ha. In 1990, the prevailing exchange rate was Rs 17.51 to US$ 1 (Reserve Bank & India Bulletin 1990, 1991 –various issues). We chose the 1990 conversion rate because Bhalla & Singh (2001) and CMIE (2000) had reported their data keeping 1990 as the base year. In addition to regression equations, we have used GIS tools to visually represent our finding wherever possible.

4 INDIA: REGIONAL PERSPECTIVE

4.1 *Geographic extent*

India is the seventh largest country in the world. It has an area of about 3,200,000 km^2 and a population of 1,027 million (Census of India 2001). Lying entirely in the Northern Hemisphere, the mainland extends between latitudes 8°4' and 37°6' North and longitude 68°7' and 97°25' East. The mainland comprises of three well-defined regions viz. the great mountain zone in the north, the Indo-Gangetic plains in the middle and the peninsular plateau in the south.

At a political level, India is divided into 28 States and 7 Union Territories. The major Indian states are: Andhra Pradesh, Assam, Arunachal Pradesh, Bihar, Chattisgarh, Goa, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Mizoram, Meghalaya, Manipur, Nagaland, Orissa, Punjab, Rajasthan, Sikkim, Tamil Nadu, Uttar Pradesh, Uttaranchal and West Bengal. The Union Territories are Andamand and Nicobar Islands, Chandigarh, Delhi, Daman and Diu, Dadra and Nagar Haveli, Lakshadweep Islands and Pondicherry (see Fig. 1).

Figure 1. Political map of India (http://www.mapsofindia.com).

4.2 *Climate and rainfall*

The climate of India may be broadly described as tropical monsoon type. There are four seasons in India: a) Cold weather season (December-February); b) Hot weather season (March-May); c) Rainy season or South-West monsoon season (June-September); and d) Retreating monsoon season or North-East monsoon season (October-November).

The bulk of rainfall in India occurs during the four monsoon months of June to September. Rainfall is highly erratic and there is a wide spatio-temporal variability across regions and years. In any given year, one part of the country could be affected by deficit rainfall, while some others may face floods. However, on an average, the country receives more than 1,000 mm of rainfall every year. Potential evapotranspiration ranges from 1,400 to 1,800 mm in the greater part of the country. It is higher in the arid Western parts of the country and considerably lower in coastal areas and humid northeastern regions. Figures 2–3 show the annual rainfall map and climatic regions map of India.

4.3 *Groundwater resources: occurrence and use*

India is a vast country with diversified geological, climatological and topographic conditions, giving rise to differential groundwater occurrence in different parts of the country. The aquifer map (Fig. 4) depicts the salient features of the hydrogeological environment and aquifer potential in India. The varied modes of groundwater occurrence in the country may be broadly classified as:

a) Porous formations comprising unconsolidated and semi consolidated sediments. Aquifers are both continuous and discontinuous and very often interconnected with moderate to very high yield potentials.
b) Consolidated and fissured formation, where aquifers are mostly discontinuous and have limited yield potential.

In India, groundwater development is generally restricted to the shallow zone within a depth of 50 m and is mostly at the private initiative. The level of groundwater development in India has been calculated as the ratio of net yearly draft to total utilizable groundwater resources for irrigation. It can be expressed as:

Level of groundwater development (%) = (Net Yearly Draft/Utilisable resource for irrigation) × 100

For the purpose of clearance of schemes by financial institutions, categorization of areas based on level of groundwater development has been recommended as shown in Table 1.

Table 1. Categorization of districts based on level of groundwater development.

Category of areas	% groundwater development
White	< 65%
Grey	65% but < 85%
Dark	85% but < 100%
Over-exploited	> 100 %

Source: CGWB (1995).

The total rechargeable groundwater resources in the country are computed as 431,900 Mm^3. The available groundwater resource for irrigation is 360,806 Mm^3, of which the utilizable quantity is 324,726 Mm^3. Table 2 shows the utilisable groundwater for irrigation and the level of groundwater development in major states of India (CGWB 1995).

Table 2. Utilisable irrigation potential and level of groundwater development in major Indian states (as on 1993).

States	Utilisable GW for irrigation (Mm^3)	GW development (%)
Andhra Pradesh	26,998	23.64
Bihar	25,643	19.19
Gujarat	15,588	41.45
Haryana	6,523	83.80
Karnataka	12,382	31.26
Kerala	5,928	15.28
Madhya Pradesh	38,929	16.49
Maharashtra	22,923	30.39
Orissa	15,301	8.42
Punjab	15,111	93.85
Rajasthan	9,642	50.63
Tamil Nadu	20,189	60.44
Uttar Pradesh	64,123	37.67
West Bengal	17,665	24.18
All India	324,726	31.92

Source: CGWB (1995).

4.4 *Legal aspects of groundwater*

Under India's Constitution, water is a state subject, under the jurisdiction of respective state governments. At the implementation level, groundwater lying underneath a person's land is fully under his control. This has its origin in the *dominant heritage* principal implicit in the Transfer of Property Act IV of 1882 and the Land Acquisition Act of 1894. Under the law, the owner of the land lawfully owns groundwater occurring underneath, and the tenancy law governs its use and disposition. This means that groundwater is *attached like a chattel* to land and cannot be transferred separately (Mudrakartha 1999). In recent times, The Supreme Court, which is the highest court in India, looked into the aspect of falling groundwater levels in Delhi and ordered the constitution of a Groundwater Authority to regulate and control groundwater in the country. Accordingly, the Ministry of Environment and Forests constituted the Central Groundwater Board as the Groundwater Authority and vested it with powers to pass any orders in respect of all matters concerning groundwater use in the country. The Groundwater Authority has jurisdiction all over the country and is under the administrative control of Ministry of Water Resources. However, at the practical level, groundwater belongs to the person who owns the land and s/he has total control over its use and disposal.

5 CONTOURS OF GROUNDWATER ECONOMY

Throughout Asia, the history of protective well irrigation goes back to the millennia. However, intensive groundwater use on the scale we find today is a phenomenon of the past 40 years. In India, the total number of mechanized wells and tubewells rose from less than a million in 1960 to some 19 million in 2000. In direct contrast to the formal organization of public irrigation systems, a dominant characteristic of the Indian groundwater economy is its spontaneous, private, informal nature. Private investment in groundwater irrigation can very well be compared with that of public investment in surface water. For example, over the past 50 years, against public sector irrigation investment of US$ 40,000 million (at 1995–96 prices), private groundwater investment by Indian farmers may well be of the order

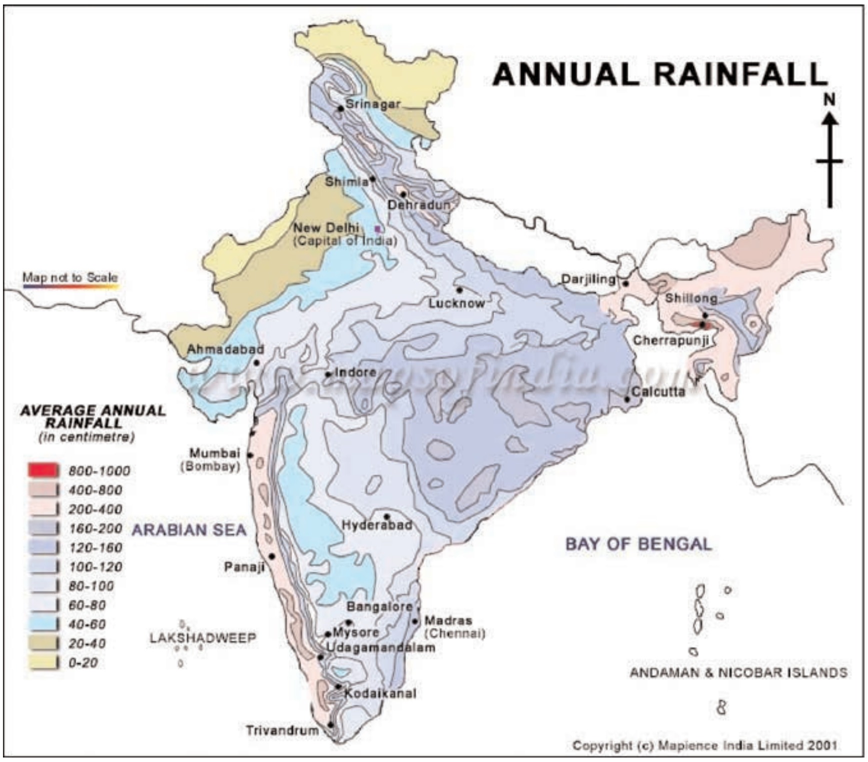


Figure 2. Annual rainfall map of India (http://www.mapsofindia.com).

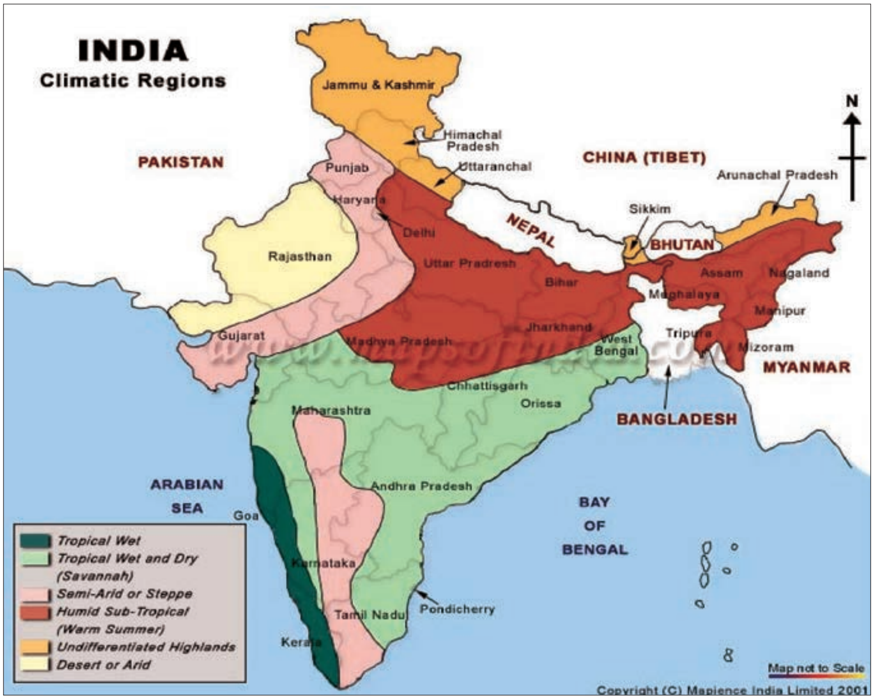


Figure 3. Climatic regions of India (http://www.mapsofindia.com).

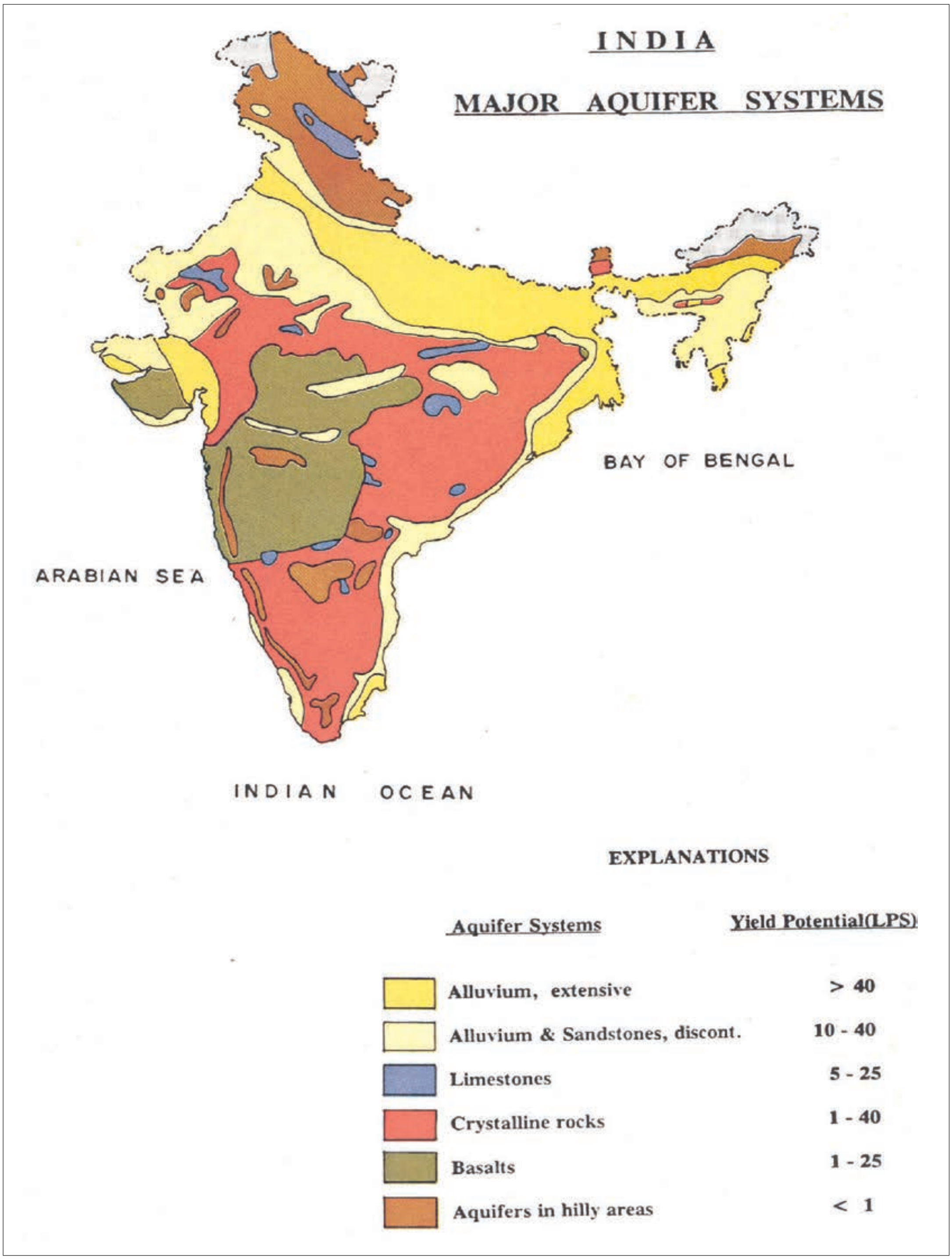


Figure 4. Major aquifer systems in India (CGWB 1995).

of US$ 19,000 million (at the rate of US$ 1,000 per piece for 19 million structures). However, the financial, economic and equity benefits from the latter are considered to be many times greater. Moreover, for a variety of reasons, groundwater irrigation is also found to be significantly more productive compared to surface irrigation. Groundwater is produced at the point of use, needing little transport, offers individual farmer irrigation *on demand* which few surface irrigation systems can offer. Due to all these factors, there has been a tremendous increase in the use of groundwater for irrigation purposes over the past two decades. This is especially true in the areas experiencing Green Revolution. A comparison of groundwater use and its dynamics in 1970s and 1990s will effectively drive home the point of increasing and intensive use of groundwater in irrigation.

5.1 *Groundwater as a source of irrigation: 1970s and 1990s*

The share of groundwater-irrigated (GWI) area to India's net cropped area (NCA) has continuously risen from 1970s to 1990s. The district level data of 251 Indian districts covering 12 states of India shows that the proportion of GWI area to NCA has gone up from 10.4% in the trienium ending 1970–73 to 21% in the period 1990–93. At the same time, the contribution of surface water irrigated (SWI) to NCA has gone up marginally from 13% of net cropped area in 1970–73 to 16% in 1990–93. In absolute terms, the groundwater-irrigated area has increased from 13 million ha to 27 million ha, an increase of 105% during the last two decades. On the other hand, area under surface water irrigation increased from 16 million ha in 1970–73 to 21 million ha, an increase of 28% during the last two decades. As a result, today, more and more number of districts have larger share of irrigated land under groundwater irrigation than surface water irrigation. Figures 5–6 show the relative share of groundwater and surface water irrigated area to net cropped area for the years 1970–73 and 1990–93.

The figures on next page clearly bring out the fact that in the majority of the Indian districts, groundwater-irrigated area is much larger than the share of surface water irrigated area. This is in spite of the huge investments made in large-scale canal irrigation projects. The very fact that groundwater irrigation has spread so rapidly, points to its being a so called *democratic resource*, its development has been need-based, rather than policy based as in the case of major surface irrigation projects. Table 3 presents the changing share of groundwater irrigation in different regions of the country.

Table 3. Changing share of groundwater-irrigated area in India: 1970–73 and 1990–93.

Year Figure	1970–73 Mean (1,000 ha)	1990–93	1970–73 Mean (1,000 ha)	1990–93
Region/ Variable	Groundwater irrigated area		Surface water irrigated area	
North	101	170	84	99
West	43	86	27	53
South	39	75	113	116
East	30	93	94	119
India	52	107	65	83

Based on source wise irrigation data obtained from ICRISAT-SEPP (1994) and net cropped area data from Bhalla & Singh (2001).

Figures 5–7 and Table 3 capture adequately the increasing share of groundwater-irrigated area in the country. The remarkable increase in area under groundwater irrigation to net cropped area is seen all across the country and particularly in Northern India –the heart of Green Revolution in the country. In many cases however, groundwater and surface water are used in conjunction and in order to see how the relative importance of each source has changed over the decades, we classified our study districts into four categories, based on the share of GWI area and SWI area to NCA. Table 4 presents the classification of districts based on the above criterion.

Table 4. Classification of districts based on area under surface water and groundwater irrigation.

Year	1970–73		1990–93	
Irrigation category*	Number of districts	% to total	Number of districts	% to total
AA	23	9.1	43	17.1
AB	27	10.8	73	29.1
BA	46	18.3	35	13.9
BB	155	61.8	100	39.9
Total	251	100	251	100

(Source: As in Table 3).
* Irrigation categories:
AA: > 20% GWI to NCA and > 20% SWI to NCA.
AB: > 20% GWI to NCA and < 20% SWI to NCA.
BA: < 20% GWI to NCA and > 20% SWI to NCA.
BB: < 20% GWI to NCA and < 20% SWI to NCA.

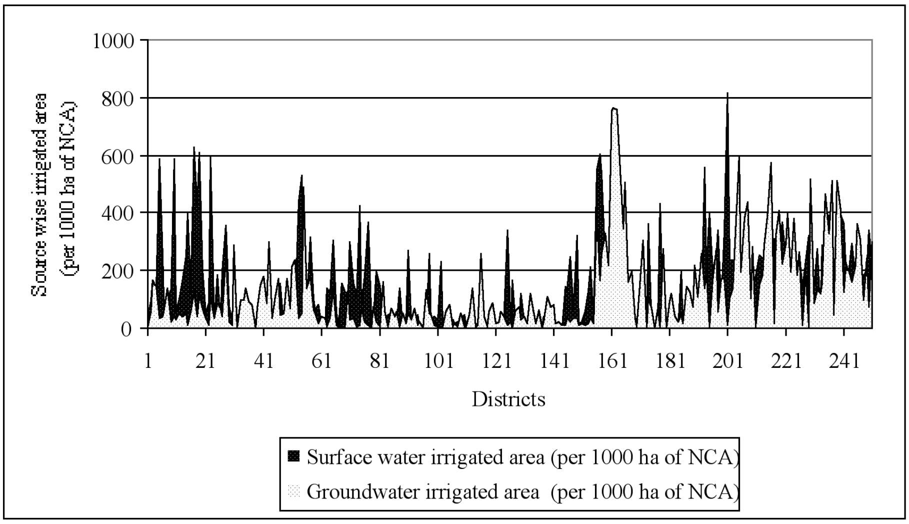


Figure 5. District wise area under surface water irrigation and groundwater irrigation to net-cropped area: 1970–73.

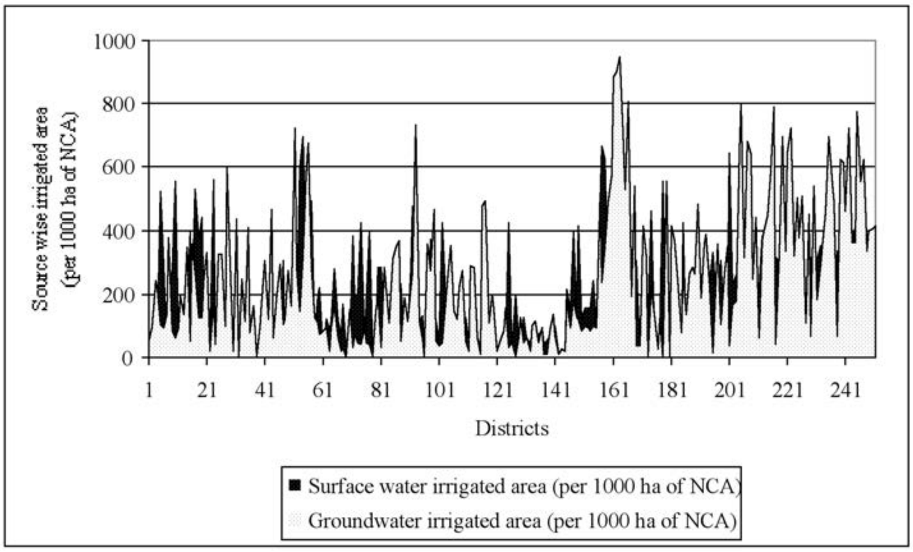


Figure 6. District wise area under surface water irrigation and groundwater irrigation to net-cropped area: 1990–93.

From Table 4 it is seen that the number of districts in the AB category (more than 20% groundwater-irrigated districts and less than 20% surface water irrigated districts) has gone up considerably during this time, from mere 27 districts in 1970–73 to 73 in 1990–93. Similarly, the number of districts with both above 20% surface water irrigated area and groundwater-irrigated area (category AA) has gone up from 23 in 1970–73 to 43 in 1990–93. At the same time, the districts with more than 20% of net cropped area under surface water irrigation and less than 20% area under groundwater irrigation (category BA) has gone down from 46 in 1970–73 to 35 in 1990–93. This clearly shows the growing importance of groundwater as a source of irrigation in India. Tables 3–4 together capture the increasing share of groundwater irrigation in India during the post Green Revolution period. In fact, it has been suggested

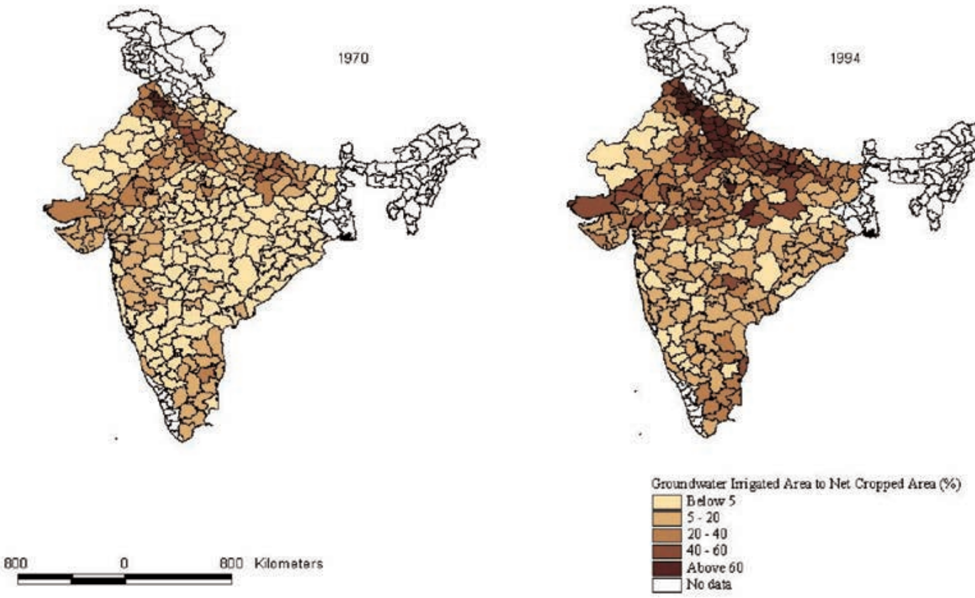


Figure 7. Groundwater-irrigated area as percentage of net cropped area in India: 1970 and 1994.

by scholars like Dhawan (1982), that the spread of Green Revolution in North India is explained more by the spread of modern pump and tubewell technologies than development of surface irrigation. All in all, groundwater is much more important today as a source of irrigation than it was 30 years ago.

6 GROUNDWATER AND AGRICULTURAL PRODUCTIVITY

Since groundwater is available on demand and offers its users control over timing and quantum of water application, several hypotheses have gained currency. The most prevalent ones in India are:

a) Ouput/m^3 of water from groundwater systems is greater than output/m^3 of water from surface irrigation systems. This is a widely asserted hypothesis, but due to data constraints about actual water use, not much macro level work has been done to test this hypothesis. Recently a study at Andalusia, Spain, showed that groundwater is five times more productive than surface water, when measured in terms of €/m^3 (Hernández-Mora *et al.*, this volume).

b) Output/ha of groundwater-irrigated land is greater than output output/ha of surface water irrigated land, *ceteris paribus*. Several studies support this hypothesis, especially at the field level and few at the macro level. Dhawan (1989) estimated the land productivity per net hectare of net cropped area for canal irrigated and groundwater-irrigated areas in Punjab and Tamil Nadu for three points of time and concluded that productivity in groundwater-irrigated area was high throughout by almost 1.5–2 times. Similar evidences were documented in a number of early studies in Pakistan (Meinzen-Dick 1996) and in Gujarat and Eastern Uttar Pradesh in India (Shah 1993). Due to reliability of supply, groundwater irrigation encourages complimentary investments in fertilizers, pesticides and high yielding varieties, leading to higher yield (Kahnert & Levine 1989). This is primarily due to the fact that groundwater irrigation is available on demand, and is therefore more reliable and timely compared to other sources of irrigation; and because its use entails significant incremental cost of lift, farmers tend to economize on its use and maximize application efficiency.

c) Groundwater's contribution to agricultural production has risen faster than surface irrigation systems because, firstly, groundwater irrigation is inherently more productive and secondly area under groundwater irrigation has expanded faster than any other irrigation source. This hypothesis has not been tested as of yet and it is particularly important in a country like India where groundwater irrigation dominates irrigated farming. There has been no systematic investigation of groundwater's contribution to agricultural production growth at the macro level. We propose to test the hypothesis (using district level data for 1970s and 1990s) that groundwater contributes more to agricultural wealth creation than any other irrigation source and that its contribution has gone up significantly in the last two decades and if trends are anything to go by, this will hold true for the decades to come.

This paper presents the first tentative macro-level test ever offered to the hypothesis that groundwater irrigation contributes more to agricultural production and that its contribution has gone up steadily during the last two decades. We have used data compiled by Bhalla & Singh (2001) for 251 districts (1960s base) of India covering 12 major states of India. These are Andhra Pradesh, Bihar (including Jharkhand), Gujarat, Haryana, Karnataka, Madhya Pradesh (including Chattisgarh), Maharashtra, Orissa, Punjab, Rajasthan and Uttar Pradesh (excluding hilly districts, now Uttaranchal). Bhalla & Singh (2001) have calculated value of production for 35 crops at 1990 base price and we have divided it by net sown area under these 35 crops in a district to arrive at district wise productivity (US$/ha of NCA) values.

6.1 *Contribution of groundwater to agricultural production: result of regression equation for the periods 1970–73 and 1990–93*

Groundwater has increasingly become an important source of irrigation and majority of the Indian districts has more land under groundwater irrigation than under any other source. This would naturally mean that the contribution of groundwater to India's agricultural output would increase many-fold, keeping pace with the increase in area under groundwater irrigation. In this section, using OLS regression techniques, we try to test the hypothesis that the contribution of groundwater to total agricultural production has increased from the 1970s to 1990s and that in many regions of India, groundwater's contribution to agricultural productivity now exceeds that of even surface water's contribution. The model specification used is as follows:

$$Y = \alpha + \beta X1 + \chi X2 + \delta X3 \qquad (1)$$

where Y = average agricultural productivity (US$/ha) in years 1970–73 and 1990–93; X1 = fertilizer use (tons/10^3 ha of NCA); X2 = surface water irrigated area per 10^3 ha of NCA; X3 = groundwater-irrigated area per 10^3 ha of NCA; α = intercept of the equation; and β, χ and δ = regression coefficients of X1, X2 and X3, respectively.

Regression was run separately for the periods 1970–73 and 1990–93. The results are summarized in Tables 5–6 respectively for the years 1970–73 and 1990–93.

Table 5. Inter district variations in agricultural productivity (US$/ha), 1970–73. All India and regions.

Variables/ Region	Estimates of regression coefficient				
	India	North	West	South	East
Fertilizer use (tons/ 10^3 ha of NCA)	4.18* (0.589)	3.17* (0.676)	4.61* (0.549)	4.98** (0.579)	3.45** (0.513)
SWI area (ha/10^3 ha of NCA)	0.31* (0.304)	0.25* (0.290)	0.22* (0.241)	0.21 (0.192)	0.03 (0.52)
GWI area (ha/10^3 ha of NCA)	0.11** (0.104)	0.12*** (0.184)	0.23** (0.212)	0.02 (0.006)	0.27*** (0.319)
Constant	119.9*	173.1*	89.5*	140.8*	200.5*
R^2	0.713	0.732	0.506	0.548	0.672
Number of observations (N)	251	66	112	47	26

Based on data compiled from Bhalla & Singh (2001).

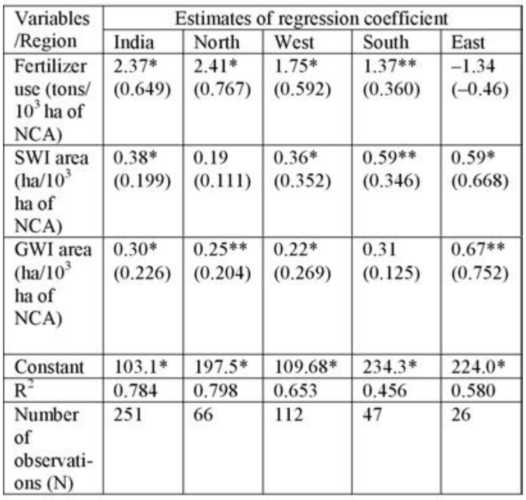
Dependent variable is value of agricultural productivity (US$/ha of NCA) for 35 crops.

Figures in parentheses are standardized coefficients or beta.

*, ** and *** indicate coefficients significant at 1%, 5% and 10% level of significance respectively for two tailed t-test.

Tables 5–6 show the result of regression equation, for all India and regional level. Comparing the 1970–73 and 1990–93 equations makes it quite evident that the relative importance of groundwater as a determinant of agricultural productivity has gone up very significantly during the last two decades. In 1970–73, one unit increase in area under surface water irrigation led to an additional gain of US$ 0.31 per ha and this has increased marginally to US$ 0.38 per ha in 1990–93. On the other hand, adding one unit of groundwater-irrigated area used to add up only US$ 0.11 per ha in 1970–73, as compared to US$ 0.30 per ha in 1990–93. There are of course, some regional differences, which is to be expected in a vast country like India.

Table 6. Inter district variations in agricultural productivity (US$/ha), 1990–93. All India and regions.



Variables /Region	Estimates of regression coefficient				
	India	North	West	South	East
Fertilizer use (tons/ 10^3 ha of NCA)	2.37* (0.649)	2.41* (0.767)	1.75* (0.592)	1.37** (0.360)	–1.34 (–0.46)
SWI area (ha/10^3 ha of NCA)	0.38* (0.199)	0.19 (0.111)	0.36* (0.352)	0.59** (0.346)	0.59* (0.668)
GWI area (ha/10^3 ha of NCA)	0.30* (0.226)	0.25** (0.204)	0.22* (0.269)	0.31 (0.125)	0.67** (0.752)
Constant	103.1*	197.5*	109.68*	234.3*	224.0*
R^2	0.784	0.798	0.653	0.456	0.580
Number of observations (N)	251	66	112	47	26

Based on data compiled from Bhalla & Singh (2001).

Dependent variable is value of agricultural productivity (US$/ha of NCA) for 35 crops. Figures in parentheses are standardized coefficients or beta.

*, ** and *** indicate coefficients significant at 1%, 5% and 10% level of significance respectively for two tailed t-test.

This denotes a significant incremental contribution of groundwater to average agricultural productivity in the last two decades.

However, the relative contribution of groundwater is still lower than that of surface water and this perhaps can be attributed to data anomaly and the way the data is collected. A piece of cultivated land is categorized as either surface water-irrigated or groundwater-irrigated, depending upon the mode of irrigation in the majority of the land area. For e.g. if a farmer were to irrigate 50% of his holding using surface water sources and 30% using groundwater sources, his entire parcel of land would be deemed to be surface water irrigated. There are obvious limitations to this approach. To continue with the above example, it might very well happen, that the farmer gets 80% of his production from the 30% of the land that he cultivates using groundwater, but the importance of role of groundwater can not be captured due the way data is tabulated. This creates a kind of bias against groundwater-irrigated area statistics in India and it gets under-reported in many instances.

Another way of looking at the results would be to compare the actual contribution of surface water irrigated area and groundwater-irrigated area to total agricultural productivity during the period of 1970–73 and 1990–93. In 1970–73, out of average agricultural productivity of US$ 261.4 per ha, the contribution of surface water irrigated area was US$ 41.3 per ha and that of groundwater-irrigated area was US$ 13.3 per ha. In terms of absolute figures, out of total agricultural output value of US$ 28,200 million in 1970–73, US$ 4,700 million (or 15.5%) was contributed by surface water irrigated area and US$ 1,300 million (or 4.4%) by groundwater-irrigated area for India as a whole. These figures changed drastically in 1990–93. Out of the average productivity of US$ 470.3 per ha, the contribution of surface water irrigated areas was US$ 62.6 per ha and that of groundwater-irrigated area was US$ 74.0 per ha, a jump of over 450% from 1970–73. Similarly, out of total agricultural output value of US$ 49,800 million, the contribution of groundwater-irrigated area was US$ 7,300 million (14.5%) and that of surface water irrigated was US$ 7,000 million (13.9%). The contribution of groundwater-irrigated area to total agricultural production (expressed as percentage) went up by almost 10.1 points from 4.4% in 1970–73 to 14.5% in 1990–93. At the same time, the relative contribution of surface water irrigated area to total agricultural output declined from almost 15.5% in 1970–73 to 13.9% in 1990–93 (see Table 7). This phenomenon, i.e. decline in percentage contribution of surface water irrigated area to total agricultural output and the increase in percent contribution of groundwater-irrigated area is seen across all the regions in India. Tables 7–11 show the relative contribution of groundwater and surface water irrigated area to total agricultural production for the whole of India, as well as for the four regions in the country (North, West, South and East).

All values in Tables 7–11 relate to 251 study districts spread across 12 major states of India and these 251 districts account for 81% of India's geographical area and 82% of India's population as on 2001. Total agricultural output relates to 35 major crops covering 97% of gross cultivated area in the country and is based on figures provided by Bhalla & Singh 2001.

In all the regions of India, without a single exception, the percent contribution of groundwater-irrigated area to total agricultural production has gone up by 5.3% to 11.5%, the all India average being 9.9%. Similarly, the percent con-

Table 7. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. All India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	261.4	470.3	79.9
Contribution of SW (US$/ha)	41.3	62.6	51.6
Contribution of GW (US$/ha)	13.3	74.0	456.4
Contribution of SW (million US$)	4,680	7,005	49.7
Contribution of GW (million US$)	1,320	7,297	452.8
Contribution of SW as % of total agricultural output	15.5	13.9	–1.6 percent points
Contribution of GW as % of total agricultural output	4.4	14.5	+10.1 percent points
Total agricultural output (million US$)	28,282	49,891	76.4

Table 8. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Northern India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	371.9	795.5	113.9
Contribution of SW (US$/ha)	64.7	91.1	40.8
Contribution of GW (US$/ha)	30.8	143.8	366.9
Contribution of SW (million US$)	1,552	2,169	39.8
Contribution of GW (million US$)	698	3,118	346.7
Contribution of SW as % of total agricultural output	17.5	13.3	–4.2 percent points
Contribution of GW as % of total agricultural output	7.9	19.1	+11.2 percent points
Total agricultural output (million US$)	8,373	17,059	103.7

Table 9. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Western India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	160.4	277.0	72.7
Contribution of SW (US$/ha)	15.4	37.8	145.5
Contribution of GW (US$/ha)	7.2	51.8	619.4
Contribution of SW (million US$)	925	1,932	108.9
Contribution of GW (million US$)	382	2,534	563.4
Contribution of SW as % of total agricultural output	8.6	11.6	+3.0 percent points
Contribution of GW as % of total agricultural output	3.5	15.2	+11.7 percent points
Total agricultural output (million US$)	9,164	14,098	53.8

Table 10. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Southern India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	350.1	575.3	64.3
Contribution of SW (US$/ha)	65.0	75.9	16.8
Contribution of GW (US$/ha)	7.5	41.9	458.7
Contribution of SW (million US$)	1,498	1,906	27.2
Contribution of GW (million US$)	162	996	514.8
Contribution of SW as % of total agricultural output	19.4	15.0	–4.4 percent points
Contribution of GW as % of total agricultural output	2.1	7.9	+5.8 percent points
Total agricultural output (million US$)	7,526	13,812	83.5

Table 11. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Eastern India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	255.4	382.8	49.9
Contribution of SW (US$/ha)	50.7	74.8	47.5
Contribution of GW (US$/ha)	5.9	51.8	778.0
Contribution of SW (million US$)	688	983	42.9
Contribution of GW (million US$)	79	637	706.3
Contribution of SW as % of total agricultural output	24.3	21.5	–2.8 percent points
Contribution of GW as % of total agricultural output	2.8	13.9	+11.1 percent points
Total agricultural output (million US$)	3,219	4,880	51.6

Tables 7–11 are based on results of regression equations tabulated in Tables 5–6.

tribution of surface water irrigated area has gone down in all the regions (except Western region, where it has increased by 2.8%), ranging from mere –3.3% in Eastern India to –5.3% in Northern India. This clearly brings out the growing contribution of groundwater to India's agricultural economy. In the Northern and the Western regions of the country, during the period 1990–93, contribution of groundwater to agricultural productivity (US$/ha) as well as total agricultural output (million US$), exceeds that of the contribution of surface water irrigated area (Tables 8–9). However, in Southern and Eastern India, the absolute contribution of groundwater to average productivity (US$/ha) and total output (million US$) is slightly lower than that of surface water irrigated area. This might perhaps be attributed to the nature of aquifers in Southern India (a predominantly hard rock area) and to the recent introduction (mid to late 1980s) of modern pump technology in much of Eastern India. On the whole, our analysis shows that the contribution of groundwater to agricultural productivity (US$/ha) and agricultural output (million US$), has increased many fold from 1970–73 and in many regions of the country, groundwater contributed more to agricultural wealth creation than any other source of irrigation. Our model estimates are more or less robust. It diverges substantially on both the extremes, i.e. it cannot predict the very low productivity districts and the very high productivity districts, but predicts the majority of the middle lying districts pretty well. Figures 8–9 show the actual and model predicted agricultural productivity for 251 districts in India. Figures 10–11 show the percent contribution of groundwater-irrigated area and surface water irrigated area to total agricultural output in the country for the period 1970–73 and 1990–93.

Our foregoing analysis clearly brings out the fact that groundwater's contribution to India's agricultural economy has experienced a phenomenal rise during the last two decades (1970s to 1990s) and this trend is likely to continue. During 1970–73, the contribution of groundwater-irrigated area and surface irrigated area to total agricultural output was US$ 1,320 million and US$ 4,680 million respectively and this has gone up to US$ 7,297 million and US$ 7,005 million in 1990–93. For India as a whole, the contribution of groundwater-irrigated area (both in terms of productivity measured in US$/ha and production values in million US$) is considerably higher than the contribution of surface water irrigated area in 1990–93.

6.2 *Contribution of groundwater to agricultural production: result of regression equation with pooled data for 1970–73 and 1990–93*

In the above sub section, we saw the growing importance of groundwater as a determinant of agricultural production in India. In order to bring out the change over time and to further strengthen our basic argument, we ran another regression with pooled data of both 1970–73 and 1990–93, using dummy variable for different time periods. The number of observation in this case was 502, i.e. 251 districts in each period. The model specification and the explanation are given below:

$$Y = f\{X1, X2, X3, D\} \qquad (2)$$

where Y = average agricultural productivity (US$/ha) in years 1970–73 and 1990–93; X1 = fertilizer use (tons/1,000 ha of NCA); X2 = surface water irrigated area per 1,000 ha of NCA; X3 = groundwater-irrigated area per 1,000 ha of NCA; D = dummy for years, where D = 0 for 1970–73 and D = 1 for 1990–93.

Regression equation with dummy (D) for two different periods becomes

$$Y = \alpha + aD + \beta X1 + \beta_1(DX1) + \delta X2 + \delta_1(DX2) + \gamma X3 + \gamma_1(DX3) \qquad (3)$$

When D = 0 (i.e. for values corresponding to years 1970–73), the equation becomes

$$Y = \alpha + \beta X1 + \delta X2 + \gamma X3 \qquad (4)$$

When D = 1 (i.e. for values corresponding to years 1990–93), the equation becomes

$$Y = \alpha + a + \beta X1 + \beta_1 X1 + \delta X2 + \delta_1 X2 + \gamma X3 + \gamma_1 X3 \qquad (5)$$

or,

$$Y = (\alpha + a) + X1(\beta + \beta_1) + X2(\delta + \delta_1) + X3(\gamma + \gamma_1) \qquad (6)$$

where α = initial productivity (US$/ha) in 1970–73; $\alpha + a$ = initial productivity (US$/ha) in 1990–93; a = difference in initial productivi-

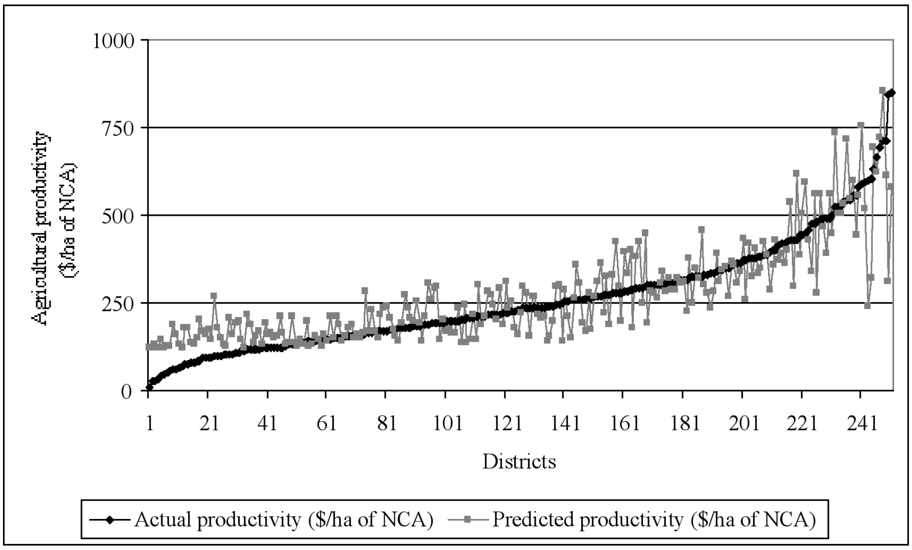


Figure 8. Actual and predicted agricultural productivity based on regression equations. All India, 1970–73.

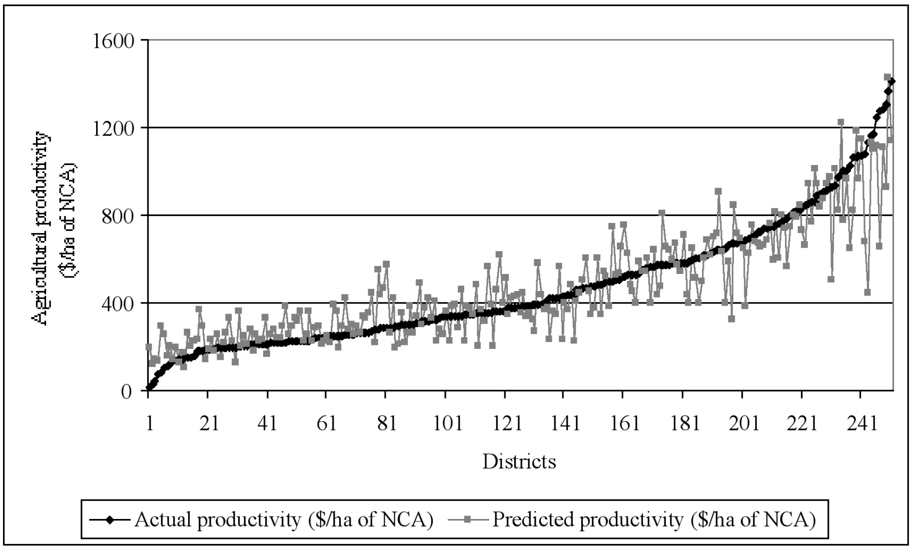


Figure 9. Actual and predicted agricultural productivity based on regression equations. All India, 1990–93.

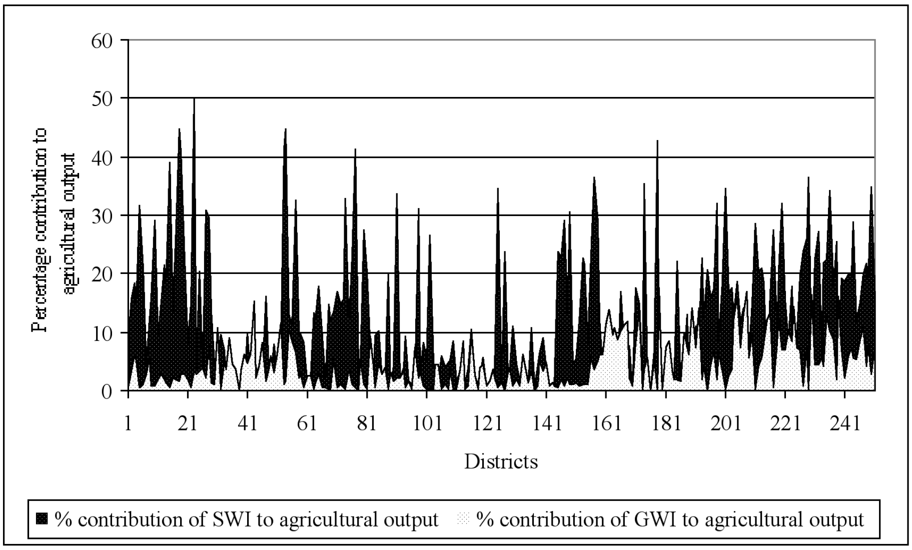


Figure 10. Contribution of groundwater and surface water irrigated area to total agricultural output. All India, 1970–73.

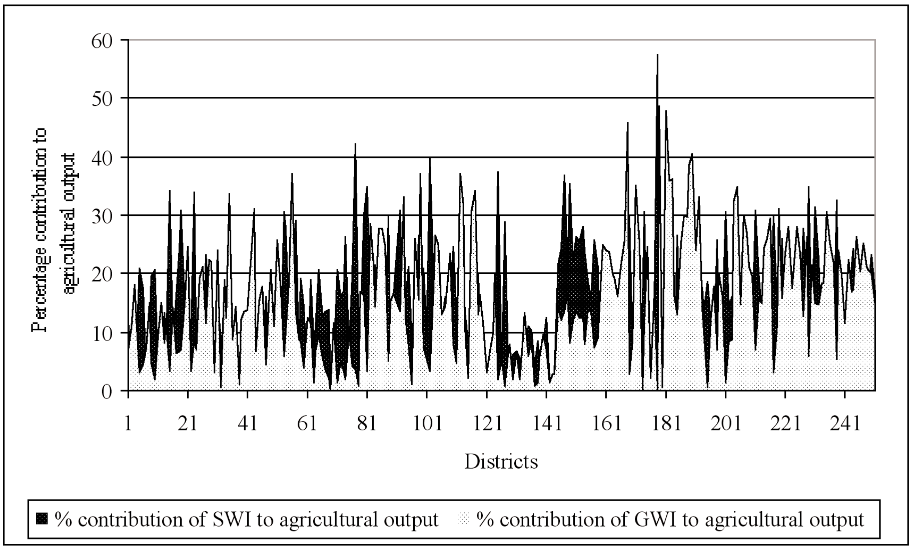


Figure 11. Contribution of groundwater and surface water irrigated area to total agricultural output. All India, 1990–93.

ty (US$/ha) between 1970–73 to 1990–93; β = effect of fertilizer consumption on productivity in 1970–73; $\beta + \beta_1$ = effect of fertilizer consumption on productivity in 1990–93; β_1 = difference in effect of fertilizer on productivity between 1970–73 to 1990–93; δ = effect of surface water irrigated area (per 10^3 ha of NCA) on productivity in 1970–73; $\delta + \delta_1$ = effect of surface water irrigated area (per 10^3 ha of NCA) on productivity in 1990–93; δ_1 = difference in effect of SWI area on productivity between 1970–73 to 1990–93; γ = effect of groundwater-irrigated area (per 1,000 ha of NCA) on productivity in 1970–73; $\gamma + \gamma_1$ = effect of groundwater-irrigated area (per 10^3 ha of NCA) on productivity in 1990–93; and γ_1 = difference in effect of GWI area on productivity between 1970–73 to 1990–93.

The regression equation result is reported below:

$$Y = 43.80^{*} - 6.18D + 1.52^{*}X1 - 0.66^{*}DX1 + 0.11^{*}X2 + \\ + 0.03DX2 + 0.04^{***}X3 + 0.069^{**}DX3 \qquad (7)$$

where $R^2 = 0.808$ and $N = 502$.

*, ** and *** denote that the coefficients are significant at 1%, 5% and 10% level of significant for two-tailed t-test.

The above equation further drives home the point about growing importance of groundwater as a contributor towards agricultural output in India. In 1970–73, the coefficient of groundwater-irrigated area to net sown area was not significant ($\gamma = 0.04$), but the difference in effect of groundwater-irrigated area on productivity ($\gamma_1 = 0.069$) is significant at 5% level. However, though the coefficient of surface water irrigated area was highly significant in 1970–73 ($\delta = 0.11$), the difference in its effect in the period 1970–73 to 1990–93 is not significant at all ($\delta_1 = 0.03$). This shows, while the contribution of groundwater-irrigated area to total agricultural productivity has increased significantly during this period, the contribution of surface water irrigated area has remained more or less stagnant.

This is a crucial finding and has far reaching policy implications, because groundwater irrigation is inherently less biased against the poor than large-scale surface irrigation projects. In India, while 76% of operational holdings are small and marginal farms (of less than 2 ha), they operate only 29% of the area. They constitute 38% of net area irrigated by wells, and account for 35% of tubewells fitted with electric pump sets (GOI 1992, as cited in World Bank & Government of India 1998). Thus, in relation to the amount of land they cultivate, the poor are better represented in ownership of groundwater related assets. Groundwater irrigation therefore can be an effective vehicle of poverty eradication as is exemplified by the impact of treadle pumps in Gangetic West Bengal and Bangladesh (Shah *et al.* 2001).

7 DETERMINANTS OF GROUNDWATER USE IN INDIA: SOME EVIDENCE

Uncomfortable questions in equity in access notwithstanding, groundwater is often called a *democratic* resource when compared to mega-dams and large-scale irrigation projects. Regrettably despite its growing significance, our understanding of the forces that drive the groundwater economy has remained limited. It is generally thought that groundwater availability is the most important determinant of groundwater use. This availability could be either due to natural recharge or due to recharge resulting from canal seepage. The second type of recharge (viz. recharge due to canal seepage) is considered very important by irrigation specialists in India who contend that groundwater use is intensive in areas of canal irrigation and that it is mostly the surface irrigation return flow and seepage from canals that is extracted by millions of private pumps in India.

However, our analysis suggests the *supply push* to be just one side of the coin. The other side is the *demand pull*, well exemplified by the relationship between population density, agricultural dynamism (denoted by past agricultural productivity values) and groundwater extraction in India. Some of the variables that possibly affect the utilization of groundwater in India are population density, general level of agricultural development (denoted by 1980–83 productivity values), institutional support like credit, net availability of groundwater resources and availability of surface water resources. On an *a priori* basis, it can be conjectured that population density, overall level of agricultural development, availability of groundwater and credit facilities will have a positive impact on groundwater use, while availability of plentiful surface water actually obviates the need for groundwater extraction. To test this hypothesis, we formulate three models: a supply side model, a demand side model and a combined model for the 1990s (roughly corresponding to the period 1990–95). The model specifications are given below:

Model 1: Supply push model.
Pump density per ha of NCA = f {Net renewable groundwater available for irrigation (m^3/ha of NCA), surface water irrigated area to NCA (%), average rainfall during monsoon months from June to August (mm)}.

Model 2: Demand-pull model.
Pump density per ha of NCA = f {Population density (persons/km^2), agricultural productivity (US$/ha) in 1980–83, agricultural credit in 1995 (US$/ha of NCA)}.

Model 3: Combined Demand and Supply Model.

Pump density per ha of NCA = f {Net renewable groundwater available for irrigation (m^3/ha of NCA), surface water irrigated area to NCA (%), average rainfall during monsoon months from June to August (mm), population density (persons/km^2), agricultural productivity (US$/ha) in 1980–83, agricultural credit in 1995 (US$/ha of NCA)}.

The results are based on observations across 225 districts of India (1960s base), with the exception of Rajasthan districts, where pump density data are not available. The results of the above three models are summarized in Table 12.

The equation in Table 12 shows the supply, demand and integrated models of determinants of pump density in India. The supply model (in the second column of Table 12) shows that as expected, pump density is a positive and significant function of groundwater availability, while surface water irrigated area and rainfall are negative functions. However, surface water irrigated area to net cropped area is significant only at 10% level in the equation. The R^2 value is quite low, which means that supply side factors only explain some 16% of the variation by themselves.

The equation in the third column of Table 12 depicts the demand dynamics of groundwater use in India. General level of agricultural dynamism (as denoted by past agricultural productivity) and density of population comes out as two most important determinant of groundwater use in the country. The explanatory power of the demand side model is much higher than the supply side model (R^2 = 0.342), thereby indicating that demand side parameters are more important in determining groundwater use than the supply side parameters. The equation in the last column of Table 12 captures both the supply and the demand side variables and quite predictably, the explanatory power of the model further increases. Combining the demand and the supply parameters of groundwater use as expressed by pump density gives us a better result than only supply side and demand side models. The most important determinant of groundwater use is the agricultural dynamism in the region, followed by population density. This brings out clearly the role that the demand side variables play in determining groundwater use in India. It can be argued that supply side factors might have influenced resource use to a large extent in the past, but at present, the demand induced growth of groundwater extraction is far more important and at times, far outweighs the groundwater availability factors. The result is what we find in the whole of North Gujarat and majority of the districts in Punjab and Haryana –groundwater extraction exceeds that of normal recharge.

The following sections look at the relationship of groundwater use and its various determinants and address some very vital concerns –viz. relationship between groundwater and surface water use and that of availability and use of groundwater.

Table 12. Inter district variation in pump density (pumps/10^3 ha of NCA): Supply side model.

Variables	Supply model	Demand model	Integrated model
Constant	72.462*	–1.221	24.085**
Groundwater availability (m^3/ha)	0.012* (0.333)		0.0046** (0.127)
SWI (per 1000 ha of NCA)	–0.067*** (–0.107)		–0.122* (–0.193)
Average monsoon rainfall (mm)	–0.044* (–0.255)		–0.0442* (–0.255)
Agricultural productivity in 1980–83 (US$/ha)		0.103* (0.357)	0.118* (0.410)
Population density (persons/km^2)		0.061** (0.192)	0.0517** (0.163)
Agricultural credit in 1995 (US$/ha)		0.119** (0.154)	0.0700 (0.090)
R^2	0.161	0.342	0.434
Number of observations (N)	225	225	225

Pump density data based on Minor Irrigation Census 1986; Net renewable groundwater for irrigation (m^3/ha of NCA), data based on CGWB (1995); Surface water irrigated area (10^3 ha), data and rainfall during monsoon months from ICRISAT-SEPP (1994); Population density based on 1991 census data; Agricultural credit based on CMIE (2000); Agricultural productivity, 1980–83 (US$/ha), data from Bhalla & Singh (2001).

*, ** and *** denote that the coefficients are significant at 1%, 5% and 10% level of significant for two-tailed t-test. The figures in parentheses are the standardized coefficients (beta).

7.1 *Pump versus population density*

Globally, intensive groundwater development has tended to get concentrated in highly populous areas. India, Pakistan, North China –three largest groundwater-using regions of the world has high population densities. Cities around the world, which typically have high population densities are intensive groundwater users. This is true for India at the national and sub national level. Figure 12 shows the density of groundwater structures fitted with mechanized pumps over population density map of India at the district level. Each dot represents 5,000 energized pumps. The map shows clearly that some of the most intensive groundwater irrigation is to be found in the most densely populated regions of India; it just happens that the upper part of the Ganga basin, with high groundwater draft –also has one of the world's best aquifers. Many parts of Southern India are far less endowed but still have high groundwater use due to their high population density. The strong relationship between pump density and population density is not difficult to explain. Much development of the surface water based irrigation development has been driven by water availability, rather than by demand for water. In India, where large proportion of the rural population live in the catchment areas of the river basins rather than the command area of the irrigation projects, depending solely on surface water irrigation systems would have created islands of affluence surrounded by vast areas of agrarian stagnation and rural poverty. With only canal irrigation, less than 20% of its farmland would have been irrigated today and Green Revolution would not have achieved wide and even spread and success that it has. In direct contrast to surface water based irrigation systems, groundwater offers scope for need-based water development throughout the river basin in a decentralized format; and therefore its development has closely followed pockets of high water demand in densely populated regions.

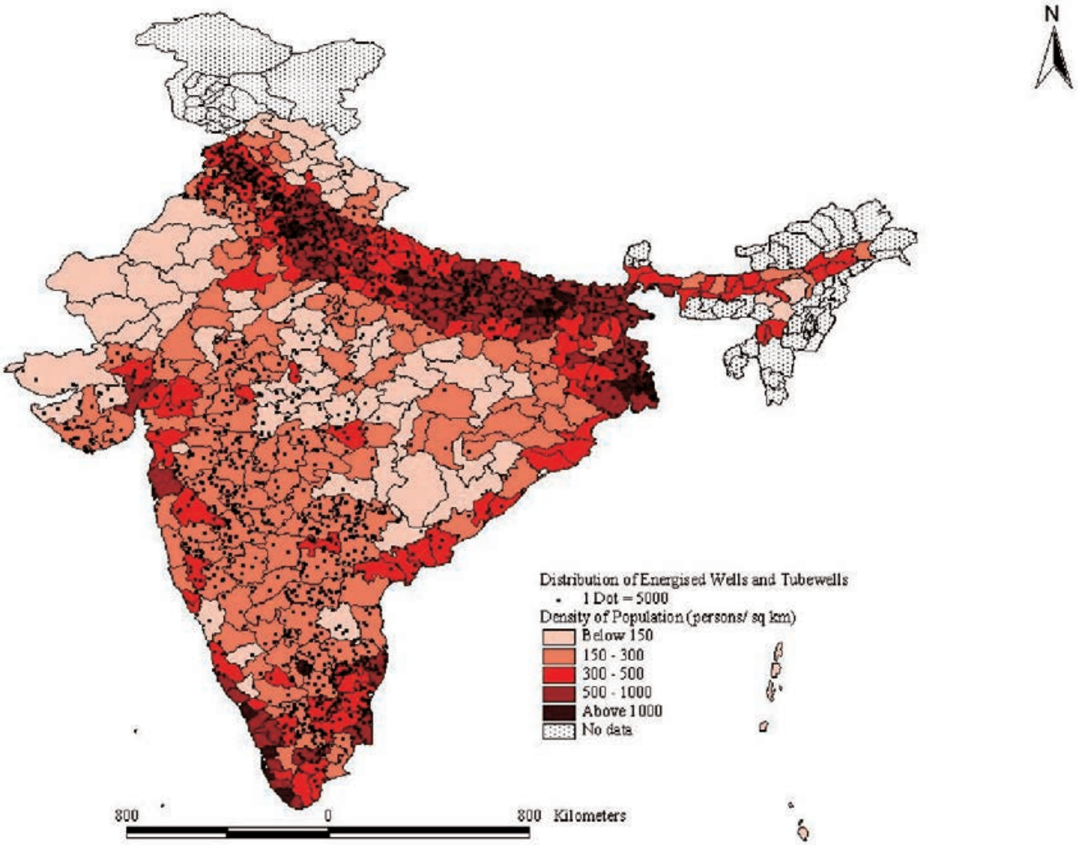


Figure 12. Density of population and distribution of energized wells and tubewells.

7.2 *Groundwater versus surface water use*

A popular notion, supported by several researchers in India, is that intensive groundwater development generally occurs in predominantly surface water irrigated area, so that the bulk of the pumped irrigation merely uses the seepage from canals and irrigation return flows. This is true for heavily canal irrigated areas, but to say that groundwater irrigation is limited only to areas with high surface water irrigation is stretching the reality too far. The development of surface water has abetted the expansion of groundwater irrigation in many parts of the country (especially the northwestern parts viz. Punjab and Haryana). However, this is not by far the most important factor in groundwater development. The massive proliferation of groundwater structures all across the length and the breadth of the country is a result of demand induced growth, where ever there are people and they demand water for irrigation, groundwater structures have come up, irrespective of canal water to supplement it, or whether there is adequate recharge every year. This is the main reason of unsustainable development of groundwater resources at various places.

Figures 13–14 show the distribution of districts according to their share of groundwater-

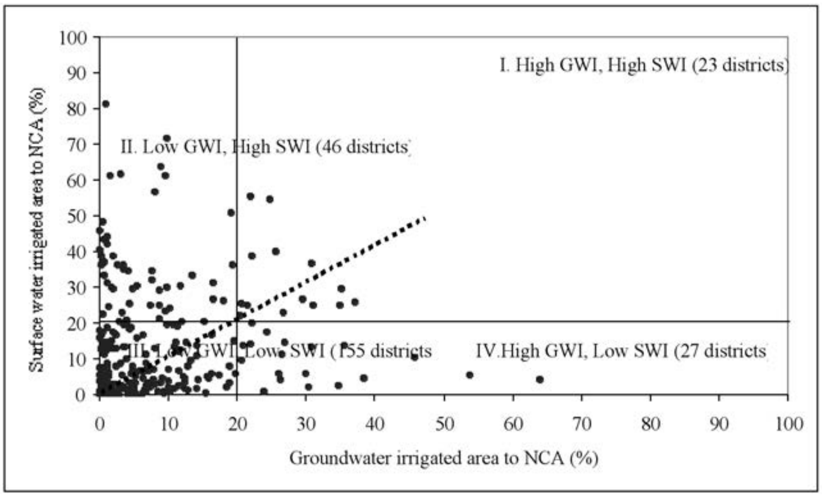


Figure 13. Groundwater *versus* surface water irrigation, 1970–73.

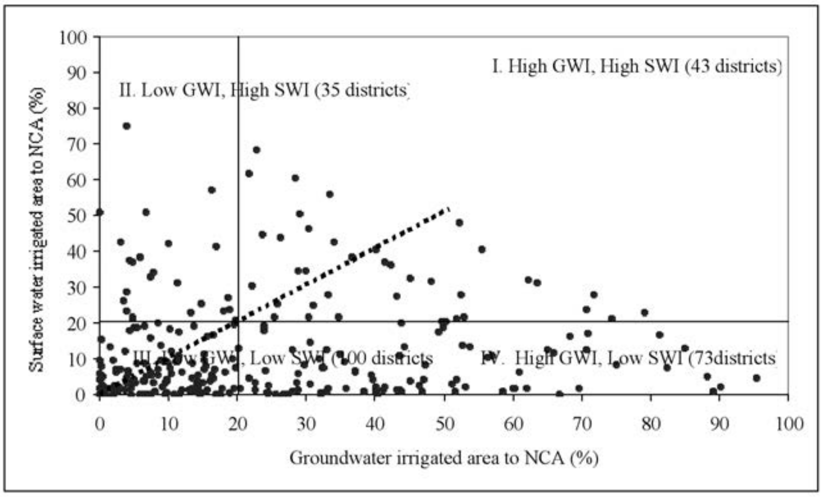


Figure 14. Groundwater *versus* surface water irrigation, 1990–93.

irrigated area and surface water irrigated area in the period 1970–73 for the years 1990–93. If use of groundwater were dependent on surface water availability, then the majority of the districts would have clustered in the quadrants III and I. To some extent, that seems to be the case in 1970–73, nevertheless, there are a number of districts in quadrants II and IV as well, showing that groundwater exploitation is rampant even in districts without much surface water sources (quadrant IV). The more dispersed nature of the scatter plot in 1990–93 bears evidence to the fact that groundwater irrigation has spread to regions of both high surface water availability (quadrant I) and low surface water availability (quadrant IV). This shows that groundwater irrigation has developed irrespective of expansion in surface water irrigation and in certain cases surface water recharge might be used for additional groundwater extraction, but this is certainly not the golden rule. Since, by far the majority of the districts fall in quadrants III and IV and not in quadrants II and I, we can surmise that groundwater development is more led by demand-pull than by supply push. The result of the regression equation (Table 12) too gives

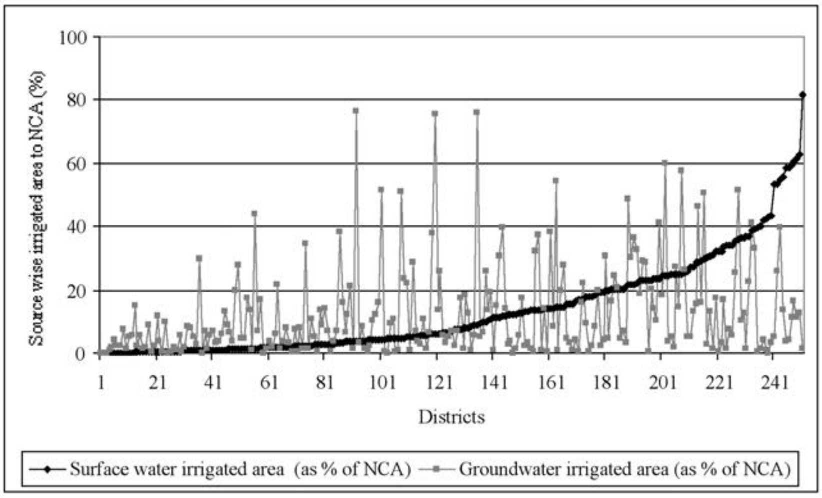


Figure 15. Districts arranged according to the share of surface water irrigated and groundwater-irrigated area to net cropped area, 1970–73.

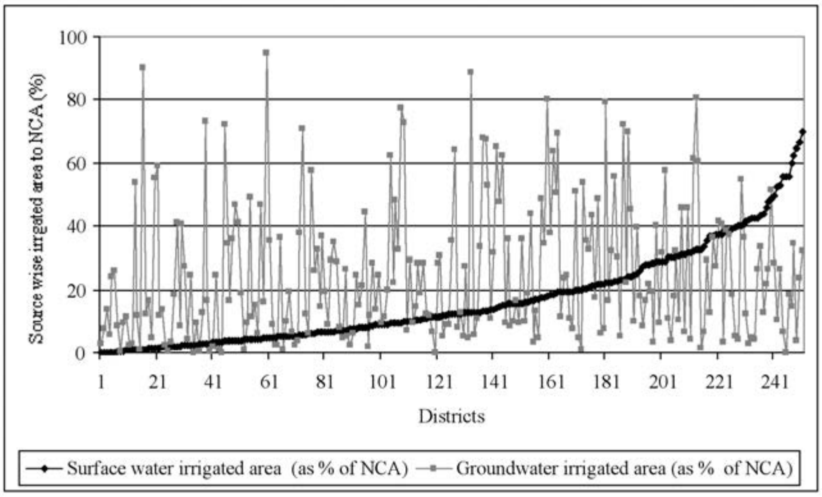


Figure 16. Districts arranged according to the share of surface water irrigated and groundwater-irrigated area to net cropped area, 1990–93.

similar result, where population density is one of the most important variables.

Figures 13–14 display a very interesting result. It is quite clear that in the beginning of the 1970s when Green Revolution was in its initial phases, groundwater extraction was indeed higher in areas with high surface water availability. But, as the phenomenon of Green Revolution spread across the country and affected new regions and crops, groundwater exploitation became quite independent of surface water irrigation sources (also see Table 4). Similarly, Figures 15–16 show the districts arranged according to the share of surface water and groundwater-irrigated area to net cropped area. The districts have been arranged in ascending order of area under surface water irrigated area to net cropped area. The figures clearly falsify the proposition that groundwater irrigation is directly related to expansion in surface water irrigation. This proposition could have held ground partially in 1970–73, but in 1990–93 and more so today (2002), groundwater irrigation is rampant even in areas where there is not much surface water irrigation to supplement it.

7.3 *Groundwater availability and use*

One of the important determinants of groundwater use is the availability of groundwater in the region. This is but natural, for one cannot use groundwater if there is none in the region. However, the opposite is not always true. It is not necessary that groundwater use is high in regions with high availability; the total amount of groundwater used also depends upon the demand for it, which in turn is related to the levels of agricultural development. To maintain some semblance of balance and sustainable use, however, it is necessary that there exist some kind of positive relationship between groundwater availability and use. In calculating groundwater availability per hectare of NCA, it was assumed that groundwater recharge has remained the same in 1990s and 1970s and consequently, 1995 groundwater recharge data were used for both the decade of 1970s and 1990s. The number of districts for which this data were available was 257, so these many districts have been included in the study. The average groundwater available for irrigation was 2,667 m^3/ha of NCA in 1970, which fell to 2,610 m^3/ha of NCA in 1995, primarily due to increase in net cropped area in the country. The districts have been divided into four categories based on groundwater availability and groundwater use. Table 13 shows the classification of districts into four categories.

Table 13. Classification of districts based on availability of groundwater for irrigation and area under groundwater irrigation, 1970–73 and 1990–93.

Year	1970–73		1990–93	
Irrigation category	Number of districts	% to total	Number of districts	% to total
AA	39	15.2	86	33.5
AB	95	37.0	49	19.0
BA	7	2.7	37	14.4
BB	116	45.1	85	33.1
Total	257	100	257	100

Based on ICRISAT-SEPP (1994) data on source wise irrigated area, and CGWB (1995) data on groundwater availability.
AB: > 2,000 m^3/ha of NCA and < 20% GWI to NCA.
BA: < 2,000 m^3/ha of NCA and > 20% GWI to NCA.
BB: < 2,000 m^3/ha of NCA and < 20% GWI to NCA.

From Table 13 it is seen that the number of districts in AA category (both high potential and high use) has gone up from 39 in 1970 to 86 in 1995, while that in AB category (high potential, low use) has come down from 95 to 49 districts. This means that more and more districts are utilizing their groundwater resources more efficiently now than in the past. However, it is the increase in the number of districts in the BA category (low potential, high use) that is a cause for concern. These districts are predominantly in the Western and Northern India. Here the potential of groundwater is low, but usage is very high giving rise to unsustainable use patterns. This is true of North Gujarat (Mehsena, Sabarkantha and Banaskantha) and a few districts of Haryana and Punjab, viz. Jind, Karnal, Mahendragarh in Haryana and Jalandhar, Kapurthala and Sangrur in Punjab. Figures 17–18 reinforce the fact that groundwater is being increasingly used in districts where is it available, and at the same time, an increasing number of districts that are not quite well endowed (quadrant IV) too are exploiting the resource. The more spread out nature of the scatter plot for 1995 shows that groundwater use is becoming more and more important and districts notwithstanding their level of groundwater potential, are extracting it for irrigation purposes. This is an unsustainable development in terms of equity and efficiency. Groundwater is being exploited at a rapid pace because of various intrinsic benefits that it gives over surface water irrigation sources. Groun-dwater exploitation and extraction is a function of predominantly *demand for irrigation* and has little to do with availability *per se*. On the other hand, surface water irrigation development has taken place keeping in mind hydrological factors, with the result that command areas of the projects are well endowed with surface water resources.

Groundwater use is therefore a function of both demand side pull (agricultural dynamism and population density) and supply side push (groundwater availability), but the demand side push far outweighs the supply side pull, giving rise to unsustainable levels of exploitation in certain parts of the country.

Figures 17–18 show that use of groundwater has become more rampant during the 1990s as compared to the 1970s. The districts, which have a high potential, are using their potential to the fullest and only a few districts have high potential and low use. The districts in the AB category (high potential and low use) are limited to the agriculturally backward states of Orissa and Madhya Pradesh and parts of South

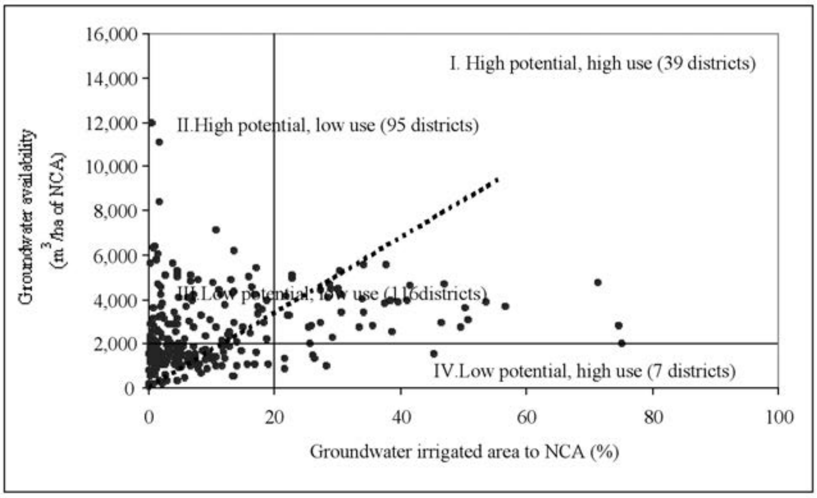


Figure 17. Groundwater availability and use, 1970–73.

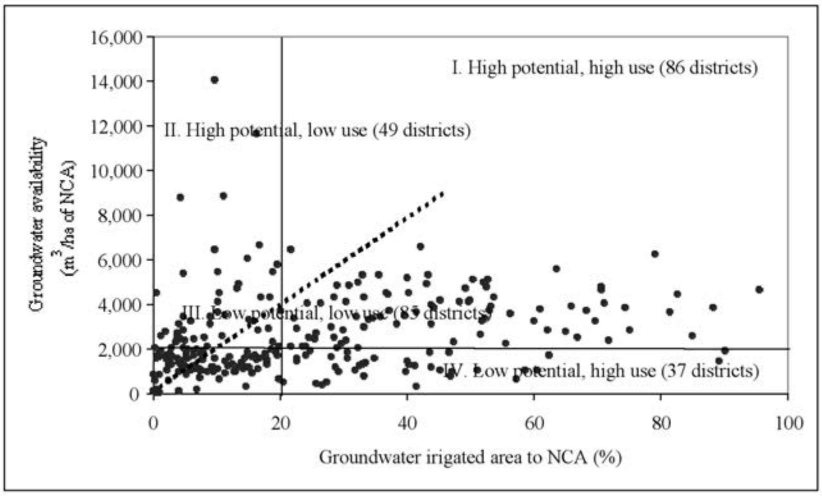


Figure 18. Groundwater availability and use, 1990–93.

Bihar (present Jharkhand). Many of these are the coastal districts of Orissa, where there is an abundant surface water resource. The number of districts over-exploiting its groundwater resources has gone up drastically during the last two decades. This has resulted in many unsustainable groundwater practices and resultant depletion and pollution of aquifers. The following section discusses the implications of excessive use and the pathology of decline.

8 SOCIO-ECOLOGICAL FALL OUT OF EXCESSIVE GROUNDWATER DEVELOPMENT

A large part of India's GDP comes from groundwater irrigation. Our estimates show that almost 14% of India's agricultural output was accounted for by groundwater irrigation in the early 1990s and if trends were anything to go by, these figures would be much higher in 2002. The groundwater socio-ecology has been at the heart of India's agrarian boom. However, this booming groundwater based agrarian economy in many parts of India is under serious threat of resource depletion and degradation. The rate at which groundwater is drawn is at many places more than the rate of natural recharge –leading to decline in water tables. The numbers of blocks in India that have overexploited their groundwater resources have gone up in the last decade or so. The number of dark and overexploited blocks (where level of groundwater development has exceeded 85% and 100% of normal recharge rates, see Section 1 for exact definition) represents a small fraction of the total area irrigated with groundwater in India. However, if the number of such block continues to grow at the present rate of 5.5% per year, by 2017–18, roughly 36% of the blocks in India will face serious problems of over-exploitation of groundwater resources.

Groundwater depletion has major environmental consequences; but it has important economic consequences too. Throughout India, continued decline of groundwater level has not only destroyed many wells, but also resulted in increasing cost of pumping. Figure 19 shows the proportion of wells and tubewells abandoned by their owners in different regions of India. In Western India, where depletion is the highest, over half of the wells are out of commission; even in other parts of the region, this proportion would steadily rise as water tables decline.

Table 14. Overexploited and dark blocks in India, 1984–85 and 1993–93.

State	1984–85	1992–93
Andhra Pradesh	0	30
Bihar	14	1
Gujarat	6	26
Haryana	31	51
Karnataka	3	18
Madhya Pradesh	0	3
Punjab	64	70
Rajasthan	21	56
Tamil Nadu	61	97
Uttar Pradesh	53	31
Total dark and overexploited blocks	253	383
Total blocks in India	4,745	5,905

Source: CGWB (1991, 1995).

Water quality and health impacts are a major cause of concern in India. Fluoride has emerged as a major problem in two-thirds of India and excess of fluoride in drinking water causes bone deformity. In the eastern part of Ganga basin –mostly in Bangladesh and Indian state of West Bengal– high arsenic content in groundwater has emerged as a major health problem. Salinity, a serious quality problem associated with modern water development has vast livelihood and health consequences. In many coastal aquifers subject to intensive groundwater development, seawater intrusion has emerged as a devastating problem. This has been very well documented in India. For example, the seawater-freshwater interface in Saurashtra region of Gujarat state in India has so far moved 4 to 7 km inland along the coast affecting more than 40,000 well structures (Bhatia 1992). However, this problem is related to management chaos than over-exploitation of groundwater *per se*. In some coastal regions (Israel, Southern California) the problem of seawater intrusion has been practically solved almost half a century ago by adopting the correct groundwater management regime. Similar problems have been recorded in Tamil Nadu's Minjur aquifer. Aquifer contamination is another major threat to groundwater quality. For instance, tannery effluents in North Arcot district of Tamil Nadu state have contaminated even the tender coconut water, with 0.2% residual chromium from tanning activities.

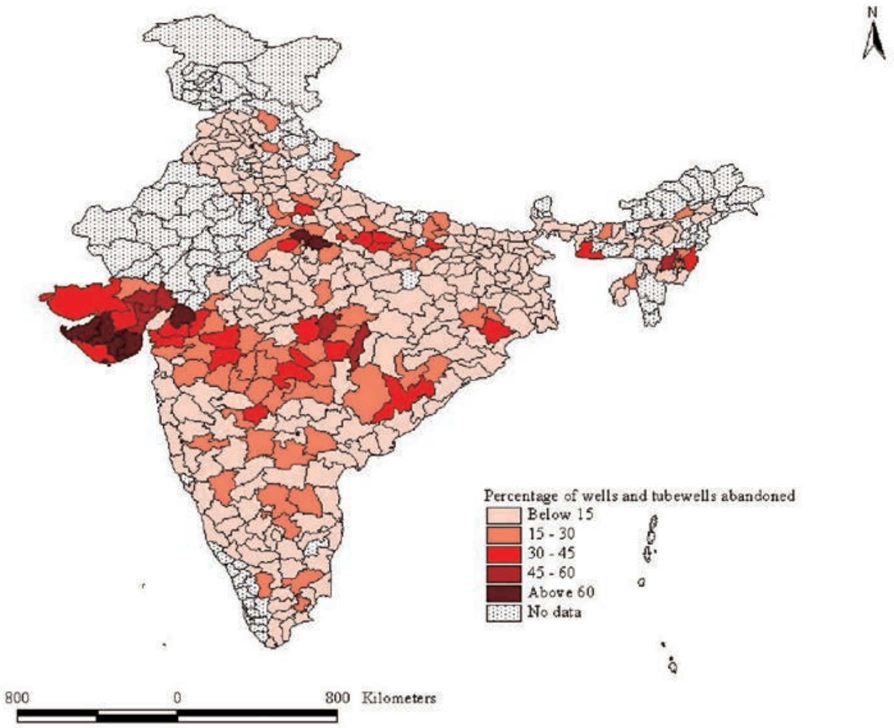


Figure 19. Percentage of wells and tubewells abandoned by their owners, India, 1986 (based on Minor Irrigation Census, GOI 1986).

8.1 *The pathology of decline*

In much of India, for example, the rise and fall of local groundwater economies follow a 4-stage progression outlined in Figure 20, which is self-explanatory. It underpins the typical progression of a socio-ecology from a stage where unutilized groundwater resource potential becomes the instrument of unleashing an agrarian boom to one in which, unable to apply brakes in time, it goes overboard in exploiting its groundwater.

The 4-stage framework outlined in Figure 20 shows the transition that Indian policymakers and managers need to make from a resource *development* mindset to a resource *management* mode. Forty years of Green Revolution and mechanized tubewell technology have nudged most of India into Stage 2-4. However, even today, there are substantial pockets those exhibit characteristics of Stage 1. The Ganga-Meghna-Brahmaputra basin –encompassing 20 districts of Terai Nepal, all of Eastern India and much of Bangladesh– offers a good example. Endowed with among the best aquifers in the world and concentrated rural poverty, the prime goal of governments in this region is to stimulate agrarian boom through groundwater exploitation (see, e.g. Kahnert & Levine 1989, Shah *et al.* 2001). But the areas of Asia that are at Stage 1 or 2 are shrinking by the day. Many parts of Western India were in this stage in 1950s or earlier, but have advanced into Stage 3 or 4. Examples galore of regions that are in Stage 3 or even 4 in South Asia. An often cited one is North Gujarat where groundwater depletion has set off a long term decline in the booming agrarian economy; here, the foresightful well-off farmers –who foresaw the impending doom– forged a generational response and made a planned transition to a non-farm, urban livelihood. The resource poor have been left behind to pick up the pieces of what was a booming economy a decade ago. This drama is being re-enacted in ecology after ecology with frightful regularity (Shah 1993, Moench 1994).

In Stage 1 and early times of Stage 2, the prime concern is to promote the profitable use of valuable, renewable resource for generating wealth and economic surplus; however, in Stage 2 itself, the thinking needs to change towards careful management of the resource. In South Asian countries, vast regions are already in Stage 3 or even 4; and yet, the policy regime ideal for Stage 1 and 2 have tended to become *sticky* and to persist long after a region moves into Stage 3 or even 4.

8.2 *Shifting gears: from resource development to management mode*

In the business-as-usual scenario, problems of groundwater over-exploitation throughout Asia will only become more acute, widespread, serious and visible in the years to come. The frontline challenge is not just supply-side innovations but to put in to operation a range of corrective

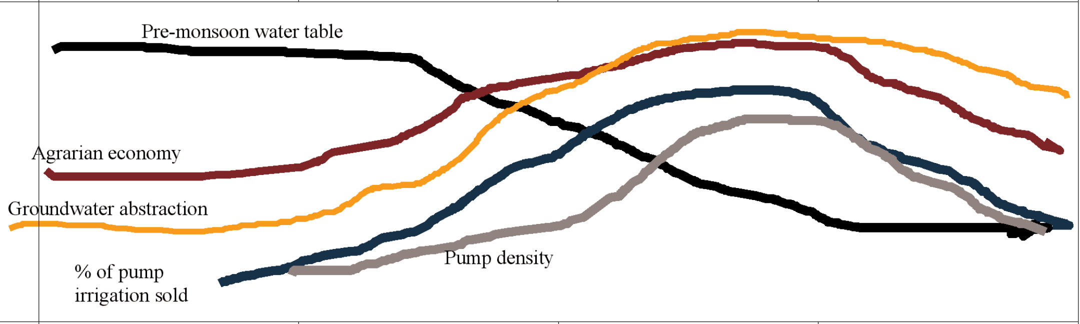
	Stage 1	Stage 2	Stage 3	Stage 4
Stages	The rise of Green Revolution and Tubewell Technologies.	Groundwater-based Agrarian Boom	Early Symptoms Groundwater Over-draft.	Decline of the Groundwater Socio-ecology with immiserizing impacts.
				
Examples	North Bengal and North Bihar, Nepal Terai, Orissa.	Eastern Uttar Pradesh, Western Godavari, Central and South Gujarat.	Haryana, Punjab, Western Uttar Pradesh, Central Tamil Nadu.	North Gujarat, Coastal Tamil Nadu, Coastal Saurashtra, Southern Rajasthan.
Characteristics	Subsistence agriculture; Protective Irrigation Traditional crops; Concentrated rural poverty; Traditional water lifting devices using human and animal power.	Skewed ownership of tubewells; access to pump irrigation prized; rise of primitive pump irrigation *exchange* institutions. Decline of traditional water lifting technologies; Rapid growth in agrarian income and employment.	Crop diversification; permanent decline in water tables. The groundwater-based *bubble economy* continues booming; but tensions between economy and ecology surface as pumping costs soar and water market become oppressive; private and social costs of groundwater use part ways.	The `bubble' bursts; agricultural growth declines; pauperization of the poor is accompanied by depopulation of entire clusters of villages. Water quality problems assume serious proportions; the *smart* begin moving out long before the crisis deepens; the poor get hit the hardest.
Interventions	Targeted subsidy on pump capital; Public tubewell programmes; Electricity subsidies and flat tariff.	Subsidies continue. Institutional credit for wells and pumps. Donors augment resources for pump capital; NGOs promote small farmer irrigation as a livelihood programme.	Subsidies, credit, donor and NGO support continue apace; licensing, siting norms and zoning system are created but are weakly enforced. Groundwater irrigators emerge as a huge, powerful vote-bank that political leaders cannot ignore.	Subsidies, credit and donor support reluctantly go; NGOs, donors assume conservationist posture zoning restrictions begin to get enforced with frequent pre-election relaxations; water imports begin for domestic needs; variety of public and NGO sponsored ameliorative action starts.

Figure 20. Rise and fall of groundwater socio-ecology in India.

mechanisms before the problem becomes either insolvable or not worth solving. This involves a transition from resource *development* to resource *management* mode (Moench 1994). Throughout Asia –where symptoms of over-exploitation are all too clear– groundwater administration still operates in the *development* mode, treating water availability to be unlimited, and directing their energies on enhancing groundwater production. A major barrier that prevents transition from the groundwater *development* to *management* mode is lack of information. Many countries with severe groundwater depletion problems do not have any idea of how much groundwater occurs, and who withdraws how much groundwater and where. Indeed, even in European countries where groundwater is important in all uses, there is no systematic monitoring of groundwater occurrence and draft (Hernández-Mora *et al.* 2001). Moreover, compared to reservoirs and canal systems, the amount and quality of application of science and management to national groundwater sectors has been far less primarily because unlike the former, groundwater is in the private, *informal* sector, with public agencies playing only an indirect role.

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

1. *Information systems and resource planning:* Most developing countries have only a limited or non-existent information base on groundwater availability, quality, withdrawal and other variables in a format useful for resource planning. The first step to managing the resource is to understand it through appropriate systems for groundwater monitoring on a regular basis, and incorporating the monitoring data in planning the use of the resource. The next is to undertake systematic and scientific research on the occurrence, use and ways of augmenting and managing the resource.
2. *Demand-side management:* The second step is to put in place an effective system for regulating the withdrawals to sustainable levels; such a system may include: a) registration of users through a permit or license system; b) creating appropriate laws and regulatory mechanisms; c) a system of pricing that aligns the incentives for groundwater use with the goal of sustainability; d) promoting conjunctive use; and e) promotion of *precision* irrigation and water-saving crop production technologies and approaches.
3. *Supply-side management:* The third aspect of managing groundwater is augmenting groundwater recharge through: a) mass-based rain-water harvesting and groundwater recharge programs and activities; b) maximizing surface water use for recharge; and c) improving incentives for water conservation and artificial recharge.
4. *Groundwater management in the river basin context:* Finally, groundwater interventions often tend to be too *local* in their approach. Past and up-coming work in IWMI and elsewhere suggests that like surface water, groundwater resource too needs to be planned and managed for maximum basin level efficiency. This last is the most important and yet the least thought about and understood, leave alone experimented with. Indeed, one of the rare examples one can find where a systematic effort seems to be made to understand the hydrology and economics of an entire aquifer are the mountain aquifers underlying the West Bank and Israel which are shared and jointly managed by Israelis and Palestinians (Feitelsom & Haddad 1998). Equally instructive for the developing world will be the impact of the entry of big-time corporate players –such as Azurix and the USA Filter in the Western USA– in the business of using aquifers as inter-year water storage systems for trading of water. As groundwater becomes scarce and costlier to use in relative terms, many ideas –such as trans-basin movement or surface water systems exclusively for recharge, which in the yesteryears were discarded as infeasible or unattractive, will now offer new promise, provided, of course, that India learns intelligently from these ideas and adapts them appropriately to its unique situation.

9 CONCLUSION AND POLICY IMPLICATIONS

Groundwater is an increasingly important contributor to rural wealth creation in India. In 1970–73, the contribution of groundwater irrigation to total agricultural productivity was lower than that of surface water irrigation. However, in 1990–93, the contribution of groundwater is much higher than that of surface water irrigation sources. Groundwater-irrigated areas contributed to 4.4% or US$ 1,320 million to total agricultural output in 1970–73. In 1990–93, its contribution has gone to US$ 7,297 million or 14.5% of total agricultural output in the country. This trend is likely to continue and contribution of groundwater is likely to have gone up further by the time this book goes for printing. Majority of the Indian districts are bringing in more and more land under groundwater irrigation. This in a way reflects the *democratic* nature of the resource-groundwater structures proliferate as and when people demand reliable irrigation. Groundwater has therefore contributed more to rural wealth creation, in spite of the very low public investments that have gone into it. The poor and the landless are relatively better represented in terms of their access to groundwater irrigation, as groundwater irrigation is inherently less biased against the poor than the mega surface water irrigation projects are. Decades of huge public investments in surface water irrigation (mostly canals) have not given as much benefits as one and a half decade of private investments in groundwater in terms of incremental yield and higher agricultural production. Groundwater irrigation provides innumerable opportunities in India, but hand in hand comes in the threat associated with over-exploitation of this rather precious resource. Over-exploitation leads to problems like salinization and pollution of fresh water aquifers, at times even endangering the basic supply of potable water. In regions of India, which have seen and experienced acute water crisis, people have come up with participatory methods to solve the problem. In countries like the USA and Australia, the presence of small number of large users and low population density creates uniquely favorable conditions for some institutional approaches to work; but these break down in India with its high population density and multitude of tiny users. For instance, a stringent groundwater law is enforced in Australia but would come unstuck in India because of prohibitive enforcement costs. Europe has high population density; but it is much more comfortable than India in its overall water balance. Moreover, at its high level of economic evolution, Europe can apply huge technological and financial muscle power to manage its natural resources which India can not; for instance, what the Netherlands spends per capita on managing its groundwater is five times the total *per capita* income of rural North Gujarat.

All in all, then, we commend a more refined and nuanced understanding of the peculiarities of India's groundwater socio-ecology and a resource management approach suited to its genius. In much of India, modern groundwater development occurred in a chaotic, unregulated fashion shaped by millions of tiny private users. Now, in many parts of India where groundwater is under worst threat of depletion there is a growing groundswell of popular action –equally chaotic and unregulated– in rainwater harvesting and local groundwater recharge. At the frontline of this movement are regions like Rajasthan and Gujarat in India where untold havoc and misery are a certain outcome if the groundwater bubble were to burst (Shah 2000). Here, rather than waiting for governments and high science to come to their rescue, ordinary people, communities, NGOs and religious movements have made groundwater recharge everybody's business. Many scientists and technocrats feel lukewarm about this groundswell of activity; but chances are that here in lie the seeds of decentralized local management of a natural resource. For long, people in India treated water like free gift of nature and saw no need to manage it; but now that they have begun to *produce* water, we find first inkling of community efforts to manage it. These popular recharge movements then offer the foundation on which India can build new regimes for sustainable groundwater management.

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