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Aditi Deb Roy
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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, 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. Groundwater based agrarian economies have resulted in unprecedented growth in rural income and agricultural productivity in many parts of the country. However, at the same time, socio-ecology of groundwater irrigation, as we call it, reflects a remarkably similar 4-stage pattern of growth and decline—from a stage where underutilized groundwater resource becomes instrumental in unleashing agrarian boom to one in which, unable to apply brakes in time, a 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.

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 and Pawar, 1987), 70-80 percent of the value of irrigated production in India may depend on groundwater irrigation. This means that a large proportion of India's agricultural GDP actually depends on groundwater. According to the World Bank and Ministry of Water Resources, GOI (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 due to 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).

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 1970's (1970-73) and 1990's (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 fold:

i. To understand the dynamics of groundwater use in agriculture
ii. 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.
iii. To spell out the factors that encourage and stimulate groundwater use and development in India.

Accordingly, this paper has been divided into four sections. Section one documents the increasing importance of groundwater irrigation in India, section 2 presents and tests the hypothesis that groundwater irrigation creates more wealth than any other source of irrigation, while section 3 delineates the factors that determine groundwater use in India. Section 4 sums up the discussion and throws in a word of caution about the possible socio-ecological fallout of excessive groundwater development.

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:

1. Bhalla et al (2001): provide data for value of 35 agricultural crops at 1990 (Rs) base year price for four decades- 1960s to 1990s. We have worked out productivity figures by dividing the value of these 35 crops (in Rs) by the net-cropped area in the district. Bhalla data span across 273 districts (1960's base), and include all states except Himachal Pradesh and North Eastern states.
2. ICRISAT-SEPP (1994) data, which they have in, turn compiled from Annual Agricultural Statistics Reports of GOI. It provides data on source wise irrigated area from 1970-71 to 1992-93 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 (1970's base)
3. 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.
4. Government of India, Minor Irrigation (MI) Census (1986) 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 the sources mentioned above. The number of districts covered using Bhalla (2001) data is 251 (1960's 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 (1960's 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 percent of geographical area of India and are home to some 82 percent 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.

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 as percent 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 section 2 and 3 to test our hypotheses. Our first model (reported in section 2) 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), we ran another regression with the same independent variables. The results are presented in section 2. 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). In addition to regression equations, we have used GIS tools to visually represent our finding wherever possible.

SECTION 1: 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. In India, for example, over the past 50 years, against public sector irrigation investment of US $20 billion, private groundwater investment by farmers may well be of the order of US $ 12 billion (@ of $600 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 1970's and 1990s will effectively drive home the point of increasing and intensive use of groundwater in irrigation.

1.1 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 show that the proportion of GWI area to NCA has gone up from 10.4 percent in the triennium ending (TE) 1970-73 to 21 percent in TE 1990-93. At the same time, the contribution of surface water irrigated (SWI) to NCA has gone up marginally from 13 percent of net cropped area in 1970-73 to 16 percent in 1990-93. In absolute terms, the groundwater-irrigated area has increased from 13 million hectares to 27 million hectares, an increase of 105 percent during the last two decades. On the other hand, area under surface water irrigation increased from 16 million hectares in 1970-73 to 21 million hectares, an increase of 28 percent points 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 1 and 2 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 above 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 the case despite huge investments made in large-scale canal irrigation projects. The 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 1 presents the changing share of groundwater irrigation in different regions of the country.

Table 1: Changing share of groundwater-irrigated area in India: 1970-73 to 1990-93

Year	1970-73	1990-93	1970-73	1990-93	1970-73	1990-93	1970-73	1990-93
Figure	Mean ('000 ha)		Mean ('000 ha)		% of NCA		% of NCA	
Region/ Variable	Groundwater irrigated area		Surface water irrigated area		Groundwater irrigated area		Surface water irrigated area	
North	101	170	84	99	27	45	23	26
West	43	86	27	53	6.3	15	5	10
South	39	75	113	116	6.5	13	19	20
East	30	93	94	119	5.7	17	18	19
India	52	107	65	83	10	21	13	16

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

Figure 1.
District wise area under surface water irrigation and groundwater irrigation to net-cropped area: 1970-73

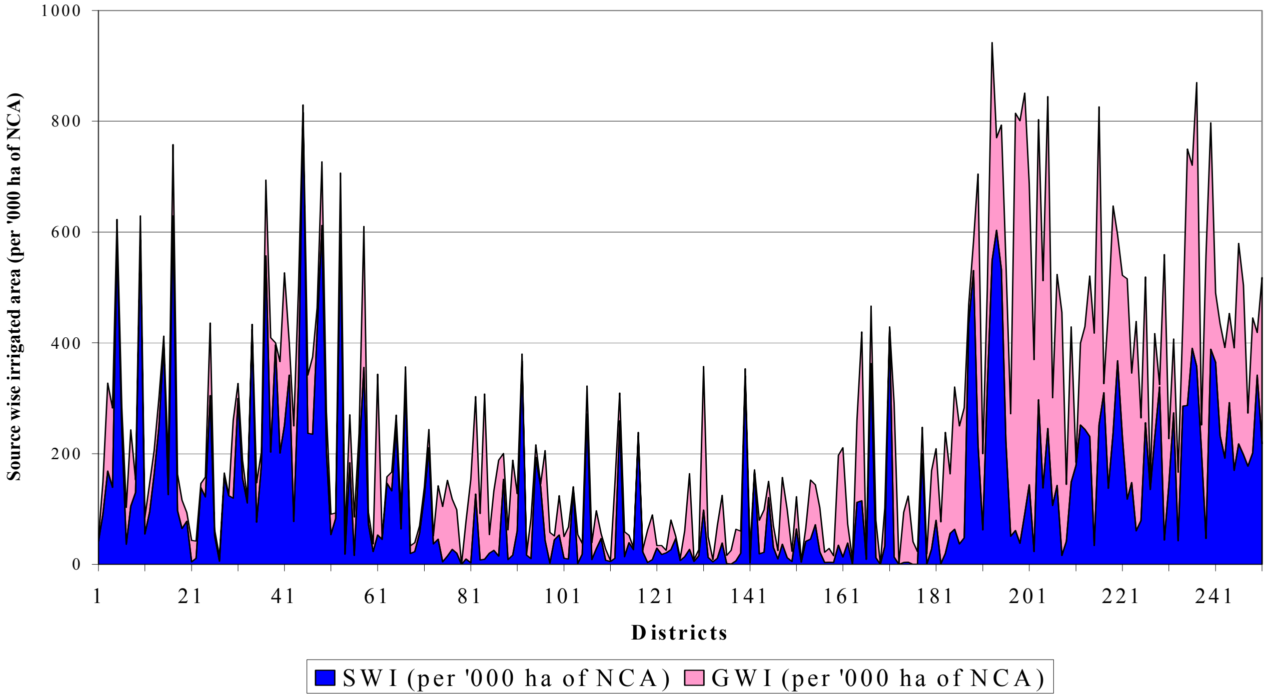
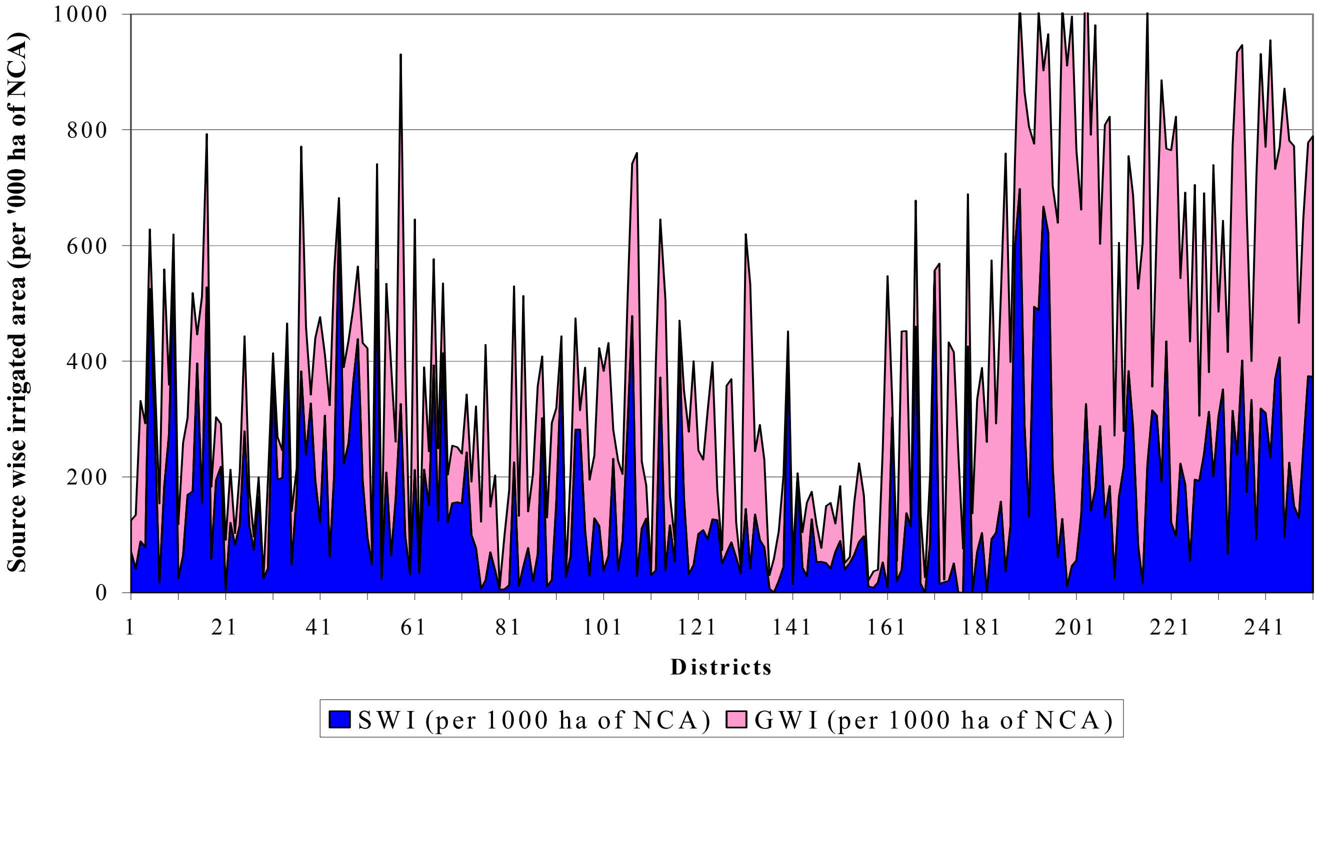


Figure 2.
District wise area under surface water irrigation and groundwater irrigation to net-cropped area: 1990-93



Figures 1, 2, 3 and table 1 capture adequately the increasing share of groundwater irrigated to total irrigated area in the country. The remarkable increase in the 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 2 presents the classification of districts based on the above criterion.

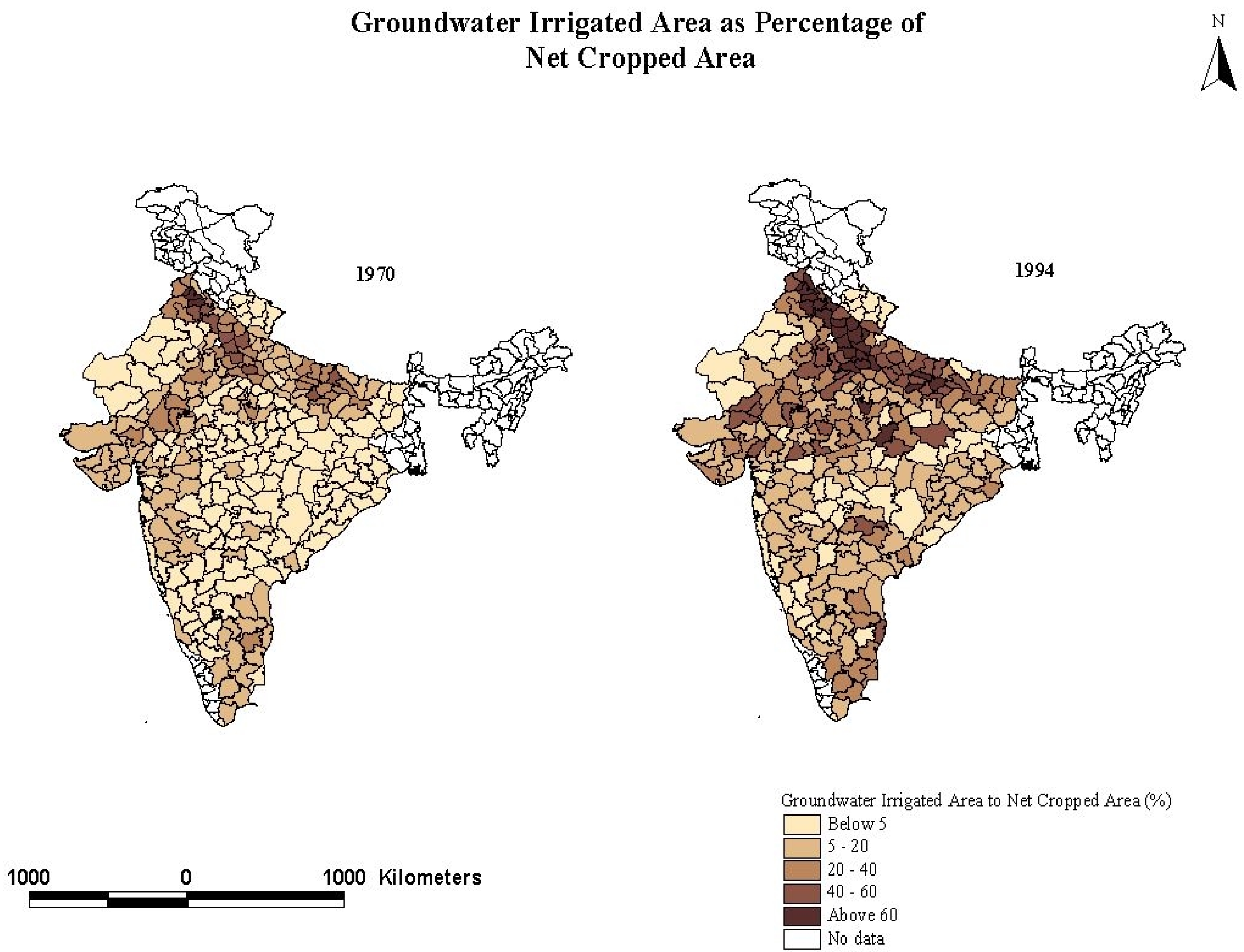
Table 2: Classification of districts based on area under surface water and groundwater irrigation, 1970-73 and 1990-93

Year	1970-73		1990-93	
Irrigation Category (based on area under groundwater and surface water irrigation to NCA)	No. of districts	% to total	No. of districts	% to total
AA: >20% GWI to NCA and > 20% SWI to NCA	23	9.1	43	17.1
AB: >20% GWI to NCA and < 20% SWI to NCA	27	10.8	73	29.1
BA: <20% GWI to NCA and > 20% SWI to NCA	46	18.3	35	13.9
BB: <20% GWI to NCA and < 20% SWI to NCA	155	61.8	100	39.1
Total number of districts	251	100	251	100

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

From table 2 it is seen that the number of districts in the AB category (more than 20% ground water 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 percent 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 1 and 2 together capture the increasing share of groundwater irrigation in India during the post-Green Revolution period. In fact, it has been suggested 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. This further consolidate the hunch that groundwater is much more important today as a source of irrigation than it was 20 years ago and, in many parts of India, this same trend is likely to continue in the future. This means that more and more land will be brought under groundwater irrigation and there will be further proliferation of groundwater structures all across the country.

Figure 3


Groundwater Irrigated Area as Percentage of
Net Cropped Area
N
1970
1994
1000
0
1000 Kilometers
Groundwater Irrigated Area to Net Cropped Area (%)
Below 5
5 - 20
20 - 40
40 - 60
Above 60
No data

SECTION 2: 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:

1. 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 Andulasia, Spain showed that groundwater is five times more productive than surface water, when measured in terms of euros/ m^3 (Hernandez-Mora et al, forthcoming).
2. Output/hectare of groundwater-irrigated land is greater than output per hectare 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 U.P 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 (Kanhert and 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.
3. 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 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 et al (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 et al have calculated value of production for 35 crops at 1990 base price and we have divided it by net sown area in a district to arrive at district wise productivity (Rs/ha of NCA) values.

2.1 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 have 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:

$$\text{Prod} = \alpha + \beta\ \text{Fert} + \chi\ \text{SWI} + \delta\ \text{GWI}$$

where, Prod = Agricultural productivity (Rs/ha of net cropped area under 35 crops)

Fert = Fertilizer consumption in tones/'000 ha of NCA

SWI = Surface water irrigated area per '000 ha of NCA

GWI = Groundwater irrigated area per '000 ha of NCA

α = Intercept of the equation

β, χ, δ = Regression coefficients of Fert, SWI and GWI respectively

Regression was run separately for the periods 1970-73 and 1990-93. The results are summarized in tables 3 and 4 respectively for the years 1970-73 and 1990-93.

Table 3: Inter district Variations in Agricultural Productivity (Rs/ha), 1970-73: All India and Region wise

Variables/ Region	Estimates of regression coefficients				
	All-India	North	West & Central	South	East
Constant	2477.226*	3124.707*	2033.605*	3160.199*	3982.906*
Fertilizer use (tones/'000 ha of NCA)	87.257* (0.614)	73.707* (0.723)	82.826* (0.499)	101.710** (0.607)	68.153** (0.486)
SWI (ha/'000 ha of NCA)	5.413* (0.269)	4.931* (0.265)	3.669** (0.206)	2.461 (0.115)	0.942 (0.125)
GWI (ha/'000 ha of NCA)	1.742*** (0.084)	1.905 (0.137)	3.162*** (0.146)	1.500 (0.025)	6.894*** (0.382)
R^2	0.693	0.743	0.385	0.501	0.750
Number of observations	251	66	112	47	26

Based on data compiled from Bhalla & Singh, 2001, dependent variable is value of agricultural productivity (Rs/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

Table 4:Inter district Variations in Agricultural Productivity (Rs/ha), 1990-93: All India and Region wise

Variables/ Region	Estimates of regression coefficients				
	All-India	North	West & Central	South	East
Constant	2434.782*	3754.707***	2458.718*	4717.842*	4693.797*
Fertilizer use (tones/'000 ha of NCA)	46.769* (0.652)	53.839* (0.767)	37.770* (0.584)	22.051*** (0.313)	-33.882*** (-0.616)
SWI (ha/'000 ha of NCA)	6.160* (0.170)	3.209 (0.087)	5.672* (0.253)	12.425*** (0.402)	10.818* (0.676)
GWI (ha/'000 ha of NCA)	5.086* (0.206)	2.637 (0.113)	4.585* (0.241)	5.367 (0.112)	15.635** (0.844)
R^2	0.742	0.684	0.556	0.464	0.580
Number of observations	251	66	112	47	26

Based on data compiled from Bhalla & Singh, 2001, dependent variable is value of agricultural productivity (Rs/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

Tables 3 and 4 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 Rs 5.4/ha and this has increased marginally to Rs 6.1/ha in 1990-93. On the other hand, adding one unit of groundwater irrigated area used to add up only Rs 1.7/ha in 1970-73, as compared to Rs 5.1/ha in 1990-93. There are of course, some regional differences, which is to be expected in a vast country like that of India. 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 Rs 5236/ha, the contribution of surface water irrigated area was Rs 734/ha and that of groundwater irrigated area was 216/ha. In terms of absolute figures, out of total agricultural output value of Rs 517 billion in 1970-73, Rs 77 billion (or 14.9%) was contributed by surface water irrigated area and Rs 21 billion (or 4.1%) from groundwater irrigated area for India as a whole. These figures changed drastically in 1990-93. Out of the average productivity of Rs 9376/ha, the contribution of surface water irrigated areas was Rs 1018/ha and that of groundwater irrigated areas was Rs 1378/ha, a jump of over 84 % from 1970-73. Similarly, out of total agricultural output value of Rs 957 billion, the contribution of groundwater irrigated area was Rs 132 billion (14%) and that of surface water irrigated was Rs 115 billion (12%). The contribution of groundwater irrigated area to total agricultural production (expressed as percentage) went up by almost 9 per cent points from 4.1 percent in 1970-73 to 13.8 percent in 1990-93. At the same time, the relative contribution of surface water irrigated are to total agricultural output declined from almost 15% in 1970-73 to 12% in 1990-93. 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 5 to 9 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).

Table 5: Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output, All India: 1970-73 and 1990-93

Year/Indicators (at 1990s INR)	1970-73	1990-93	% Change between 1970-73 to 1990-93
Average Agricultural Productivity (Rs/ha of NCA)	5236	9376	44
Contribution of SWI (Rs/ha)	734	1018	28
Contribution of GWI (Rs/ha)	216	1378	84
Contribution of SW (billion Rs)	77	115	33
Contribution of GW (billion Rs)	21	132	85
Contribution of SW as % of agricultural output	14.9	12.0	-2.9 percent points
Contribution of GW as % of agricultural output	4.1	13.8	+ 9.7 percent points
Total Agricultural Output (billion Rs)	517	957	46

Based on results of regression equations tabulated in tables 3 and 4
The figures relate to 251 study districts across 12 major states of India, which account for 81 percent of India's geographical area and 82 percent of India's total population as in 2001.
Total agricultural output relates to 35 major crops, based on Bhalla & Singh data (2001)

Table 6: Contribution of surface water irrigated and groundwater irrigated area to total agricultural output, Southern India: 1970-73 and 1990-93

Year/Indicators (at 1990s INR)	1970-73	1990-93	% Change between 1970-73 to 1990-93
Average Agricultural Productivity (Rs/ha of NCA)	7113	10954	35
Contribution of SWI (Rs/ha)	1154	1237	6.7
Contribution of GWI (Rs/ha)	121	780	84.5
Contribution of SW (billion Rs)	25.0	30.6	18.3
Contribution of GW (billion Rs)	2.6	18.1	85.6
Contribution of SW as % of agricultural output	17.7	12.5	-5.2 percent points
Contribution of GW as % of agricultural output	1.9	7.4	+ 5.5 percent points
Total Agricultural Output (billion Rs)	141	245	73.5

Source: As in table 5

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

Year/Indicators (at 1990s INR)	1970-73	1990-93	% Change between 1970-73 to 1990-93
Average Agricultural Productivity (Rs/ha of NCA)	5189	7435	30.2
Contribution of SWI (Rs/ha)	899	1196	24.8
Contribution of GWI (Rs/ha)	97	946	89.7
Contribution of SW (billion Rs)	11.3	16.1	29.8
Contribution of GW (billion Rs)	1.1	12.2	90.9
Contribution of SW as % of agricultural output	18.1	16.7	-1.4 percent points
Contribution of GW as % of agricultural output	1.8	12.6	+10.8 percent points
Total Agricultural Output (billion Rs)	63	96	34.4

Source: As in table 5

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

Year/Indicators (at 1990s INR)	1970-73	1990-93	% Change between 1970-73 to 1990-93
Average Agricultural Productivity (Rs/ha of NCA)	3226	6056	46.7
Contribution of SWI (Rs/ha)	274	591	53.6
Contribution of GWI (Rs/ha)	117	873	86.6
Contribution of SW (billion Rs)	14.2	23	38.2
Contribution of GW (billion Rs)	6.9	31	77.7
Contribution of SW as % of agricultural output	9.1	10.1	+ 1 percent point
Contribution of GW as % of agricultural output	4.4	13.5	+9.1 percent points
Total Agricultural Output (billion Rs)	155	227	31.7

Source: As in table 5

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

Year/Indicators (at 1990s INR)	1970-73	1990-93	% Change between 1970-73 to 1990-93
Average Agricultural Productivity (Rs/ha of NCA)	7328	14737	50.3
Contribution of SWI (Rs/ha)	1147	1485	22.7
Contribution of GWI (Rs/ha)	496	2675	81.5
Contribution of SW (billion Rs)	26.8	36.0	25.5
Contribution of GW (billion Rs)	10.3	57.0	81.9
Contribution of SW as % of agricultural output	17.0	11.1	-5.9 percent points
Contribution of GW as % of agricultural output	6.5	17.2	+10.7 percent points
Total Agricultural Output (billion Rs)	157	330	52.4

Source: As in table 5

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 5.5 percent points to 10.8 percent points, the all India average being 9.7 percent points. Similarly, the percent contribution of surface water irrigated area has gone down in all the regions (except in Western region, where it has gone up marginally by +1 percent), ranging from mere –1.4 percent point in Eastern India to -5.9 percent points 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 (Rs/ha) as well as total agricultural output (billion Rs), exceeds that of the contribution of surface water irrigated area (Tables 8 and 9). However, in Southern and Eastern India, the absolute contribution of groundwater to average productivity (Rs/ha) and total output (billion Rs) 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 (Rs/ha) and agricultural output (billion Rs), 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 4 and 5 show the actual and model predicted agricultural productivity for 251 districts in India. Figures 6 and 7 show the percent contribution of groundwater-irrigated area and surface water irrigated area to total agricultural output in the country from the period 1970-73 and 1990-93.

Figure 4.
Actual and Predicted Agricultural Productivity based on Regression Equations: All India, 1970-73

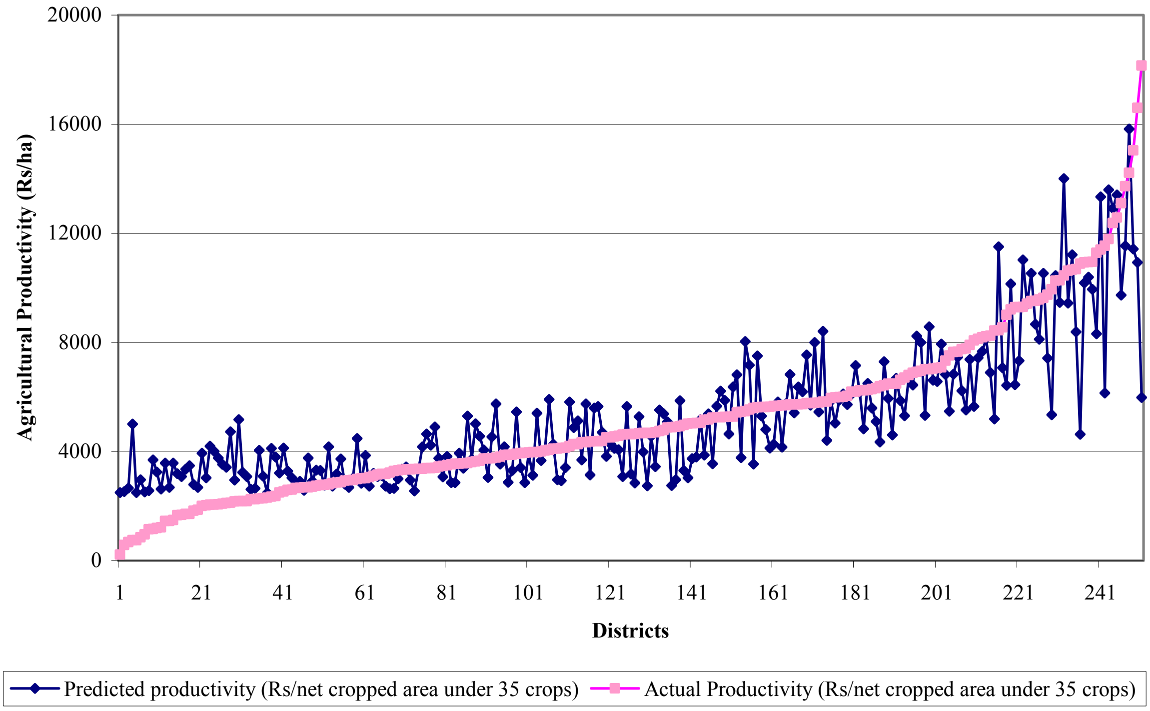


Figure 5.
Actual and Predicted Agricultural Productivity based on Regression Equations: All India, 1990-93

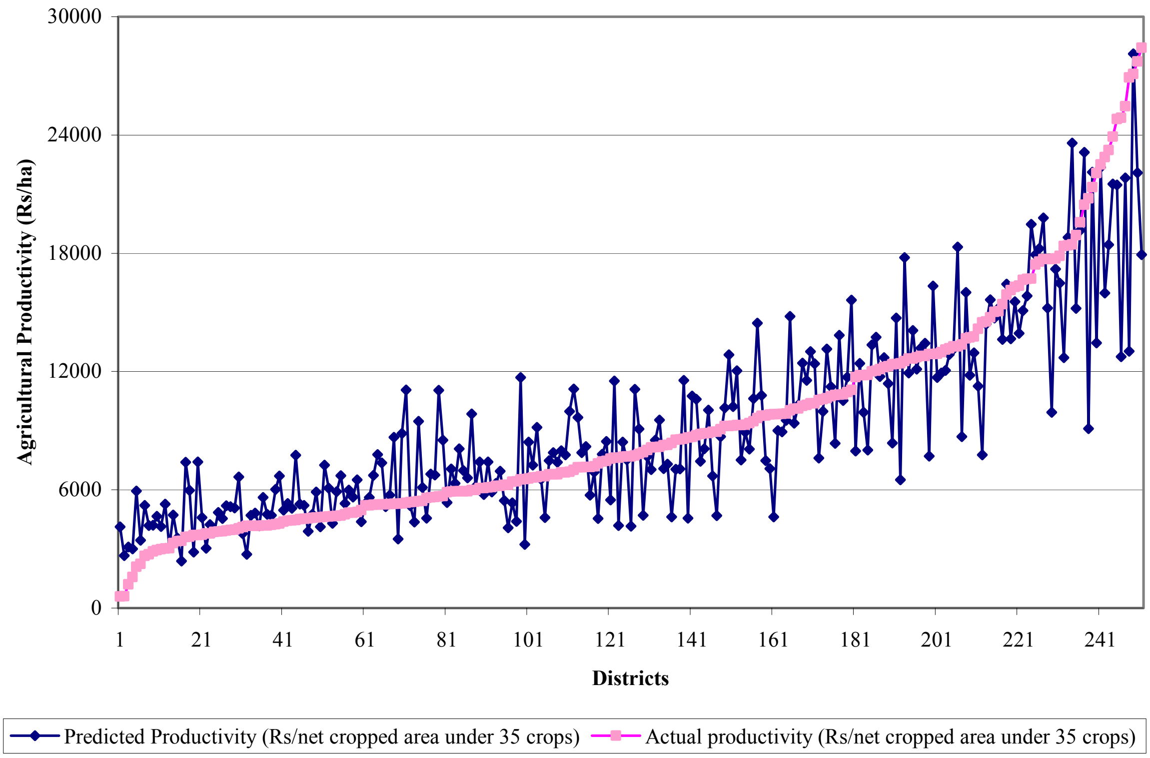


Figure 6.
Contribution of groundwater and surface water irrigated area to total agricultural output, All India: 1970-73

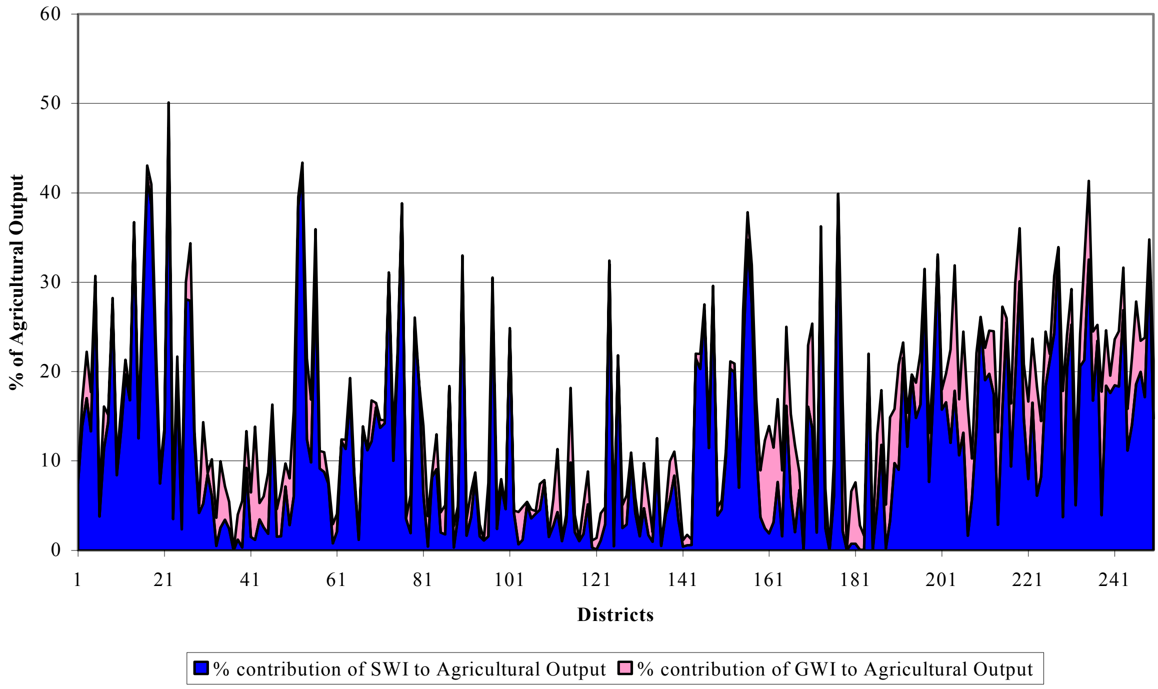
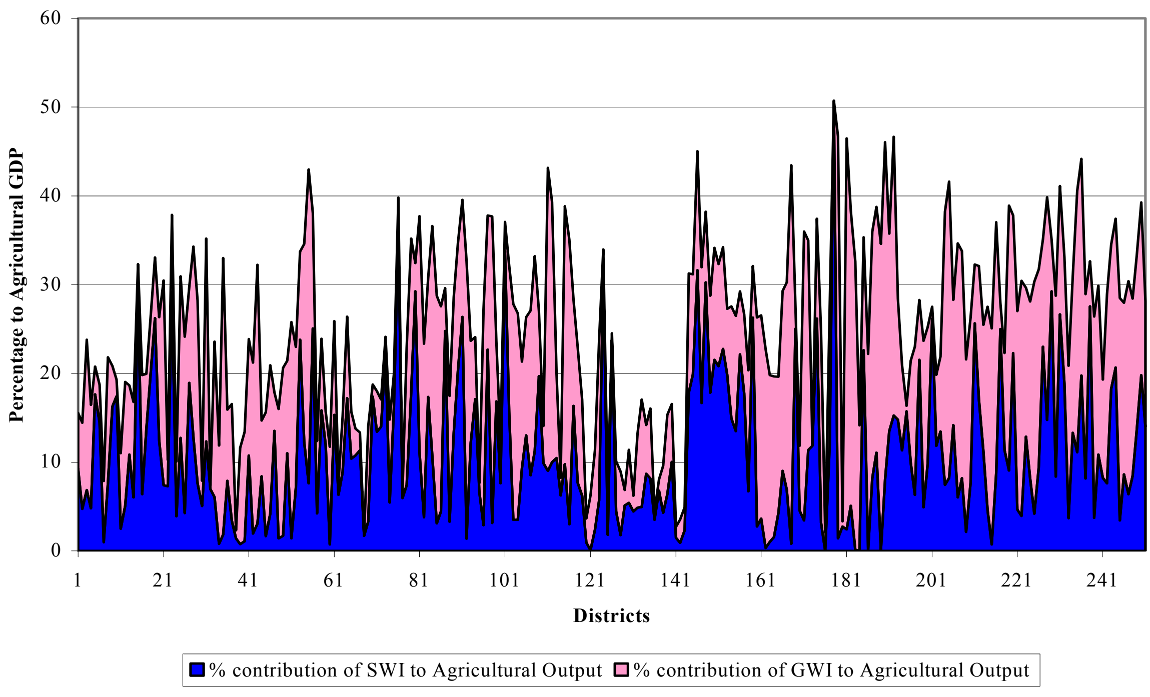


Figure 7.
Contribution of groundwater and surface water irrigated area to total agricultural output, All India: 1990-93



Our foregoing analysis clearly brings out the fact that groundwater's contribution to India's agricultural economy has seen a phenomenal rise during the last two decades (1970s to 1990s) and this trend is likely to continue. In 1970-73, the contribution of groundwater irrigated area and surface irrigated area to total agricultural output was Rs 21 billion and Rs 77 billion respectively and this has gone up to Rs 132 billion and Rs 115 billion in 1990-93. For India as a whole, the contribution of groundwater-irrigated area (both in terms of productivity measured in Rs/ha and production values in billion Rs) is considerably higher than the contribution of surface water irrigated area.

2.2 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 case was 502, i.e., 251 districts in each period. The model specification and the explanation are given below:

Y = F {X1, X2, X3 and D}

where, Y = average agricultural productivity (Rs/ha) in years 1970-73 and 1990-93
X1= fertilizer use (tones/'000 ha of NCA),
X2= surface water irrigated area per 1000 ha of NCA
X3 = groundwater irrigated area per 1000 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 become
$Y = \alpha + aD + \beta X1 + \beta_1 (DX1) + \delta X2 + \delta_1 (DX2) + \gamma X3 + \gamma_1 (DX3)$

When D=0 (i.e. for values corresponding to years 1970-73), the equation becomes
$Y = \alpha + \beta X1 + \delta X2 + \gamma X3$

When D=1 (i.e. for values corresponding to years 1990-93), the equation becomes
$Y= \alpha + a + \beta X1 + \beta_1 X1 + \delta X2 + \delta_1 X2 + \gamma X3 + \gamma_1 X3$
$= (\alpha + a) + X1 (\beta+\beta_1) + X2 (\delta+\delta_1) + X3 (\gamma+\gamma_1)$
where,
α = Initial productivity (Rs/ha) in 1970-73
$\alpha + a$ = Initial productivity (Rs/ha) in 1990-93
a = Difference in initial productivity (Rs/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 '000 ha of NCA) on productivity in 1970-73
$\delta+\delta_1$ = Effect of surface water irrigated area (per '000 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 '000 ha of NCA) on productivity in 1970-73

$\gamma+\gamma_1$ = Effect of groundwater irrigated area (per '000 ha of NCA) on productivity in 1990-93
γ_1 = Difference in effect of GWI area on productivity between 1970-73 to 1990-93

The regression equation result is reported below:
Y = 2477.226* -150.342 +87.257*X1 – 40.615*DX1 + 5.413* X2 + 0.729 DX2 +1.742 X3+ 3.831** DX3; R^2 = 0.775, N= 502

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 (γ = 1.742), but the difference in effect of groundwater irrigated area on productivity (γ_1 = 3.831) is significant at 5% level. However, though the coefficient of surface water irrigated area was highly significant in 1970-73 (δ= 5.413), the difference in its effect in the period 1970-73 to 1990-93 is not significant at all (δ_1 = 0.729). 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 constant.

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 percent of operational holdings are small and marginal farms (of less than 2 hectares), they operate only 29 percent of the area. They constitute 38 percent of net area irrigated by wells, and account for 35 percent of tubewells fitted with electric pump sets (GOI, 1992 as cited in World Bank and Ministry of Water Resources, GOI, 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).

SECTION 3: 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 (exemplified 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 situation, 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 (%), annual 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/sq km), agricultural productivity (Rs/ha) in 1980-83, agricultural credit (Rs/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 (%), annual average rainfall (mm), population density (persons/sq km), agricultural credit (Rs/capita)}

The results are based on observations across 225 districts of India (1960s base), with the exception of Rajasthan districts, where pump density data is not available. The states covered are: Andhra Pradesh, Bihar (including Jharkhand), Gujarat, Haryana, Karnataka, Madhya Pradesh (including Chattisgarh), Maharashtra, Orissa, Punjab and Uttar Pradesh (excluding hilly districts, now Uttaranchal). The results of the above three models are given in tables 10, 11 and 12.

Table 10: Inter district variation in pump density $^@$: Supply side determinant model

Variables	Estimates of regression coefficients
Net renewable groundwater for irrigation (m^3/ha of NCA)$^\#$	0.1211* (0.333)
Surface water irrigated area (‘000 ha)$^!$	-0.0676*** (-0.107)
Average rainfall during June to August (mm)$^\$$	-0.0420* (-0.255)
Constant	72.462*
R^2	0.161
Number of observations (N)	225

Dependent variable is pump density per ‘000 ha of NCA, $^@$ 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 (‘000 ha) data from ICRISAT-SEPP, 1994 and rainfall during monsoon months from ICRISAT-SEPP, 1994.
*, ** & *** 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)

The equation in table 10 shows that as expected, groundwater availability is a positive and significant function of pump density, 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 percent of the variation by themselves.

Table 11: Inter district variation in pump density @: Demand side determinant model

Variables	Estimates of regression coefficients
Population Density (persons/sq km)#	0.0609** (0.192)
Agricultural Productivity$ (Rs/ha) in 1980-83	0.00586* (0.357)
Agricultural credit (Rs/capita)!	0.00681** (0.154)
Constant	-1.221
R^2	0.342
Number of observations (N)	225

Dependent variable is pump density per '000 ha of NCA, @ Pump density data based on Minor Irrigation Census, 1986, # Population density based on 1991 census data, ! Agricultural credit based on CMIE, 2000, $ Agricultural productivity, 1980-83 (Rs/ha) data from Bhalla & Singh, 2001
*, ** & *** 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

The regression equation (table 11) 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 one of the most important determinants 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. Table 12 presented below captures both the supply and the demand side variables and quite predictably, the explanatory power of the model further increases.

Table 12: Inter district variation in pump density @: Combined Demand and Supply side model

Variables	Estimates of regression coefficients
Net renewable groundwater for irrigation (m^3/ha of NCA)	0.00462** (0.127)
Surface water irrigated area ('000 ha)	-0.122* (-0.193)
Average annual rainfall (mm)	-0.0442* (-0.255)
Population Density (persons/sq km)	0.0517** (0.163)
Agricultural Productivity$ (Rs/ha) in 1980-83	0.00674* (0.410)
Agricultural credit (Rs/capita)	0.0040 (0.090)
Constant	24.085
R^2	0.434
Number of observations (N)	225

Dependent variable is pump density per '000 ha of NCA
*, ** & *** 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

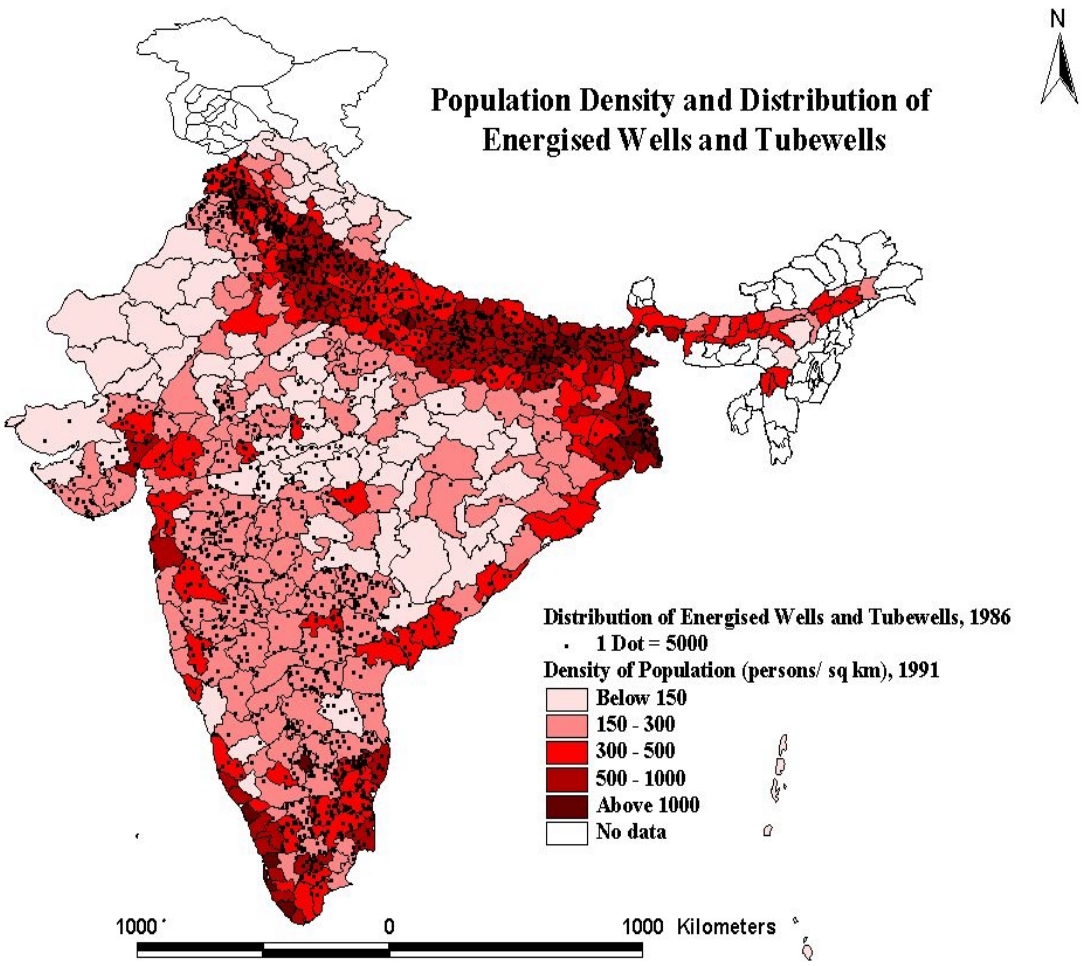
Combining the demand and the supply parameters of groundwater use as expressed by pump density gives us a better result than only supply side and demand side models (table 12). The most important determinant of groundwater use are the agricultural dynamism in the region, followed by population density. 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.

3.1 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 density. 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. The figure below (Figure 8) shows the density of groundwater structures fitted with mechanized pumps over population density map of India at the district level. Each dot represents 5000 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 percent 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 8.



3.2 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.

The figures 9 and 10 show the distribution of districts according to their share of groundwater-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, 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 II). 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 II). 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 ground water extraction, but this is certainly not the golden rule. Since, by far the majority of the districts fall in quadrants III and II and not in quadrants IV 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 similar result, where population density is the most important variable. Figure 9 and 10 displays a very interesting result. It is quite clear that in the beginning of the 1970's 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 2).

3.3 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 ground water use be high in regions with high availability- the total amount of ground water 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 ground water 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 1970's and 1990's.

Figure 9.
Groundwater versus surface water irrigation, 1970-73

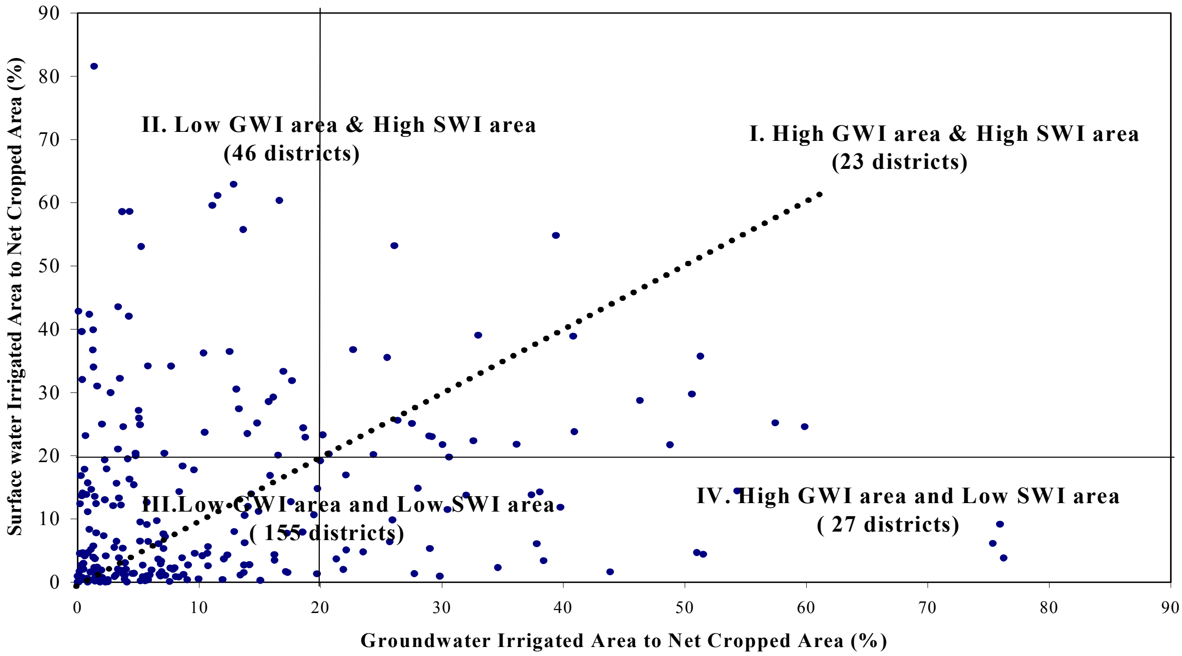
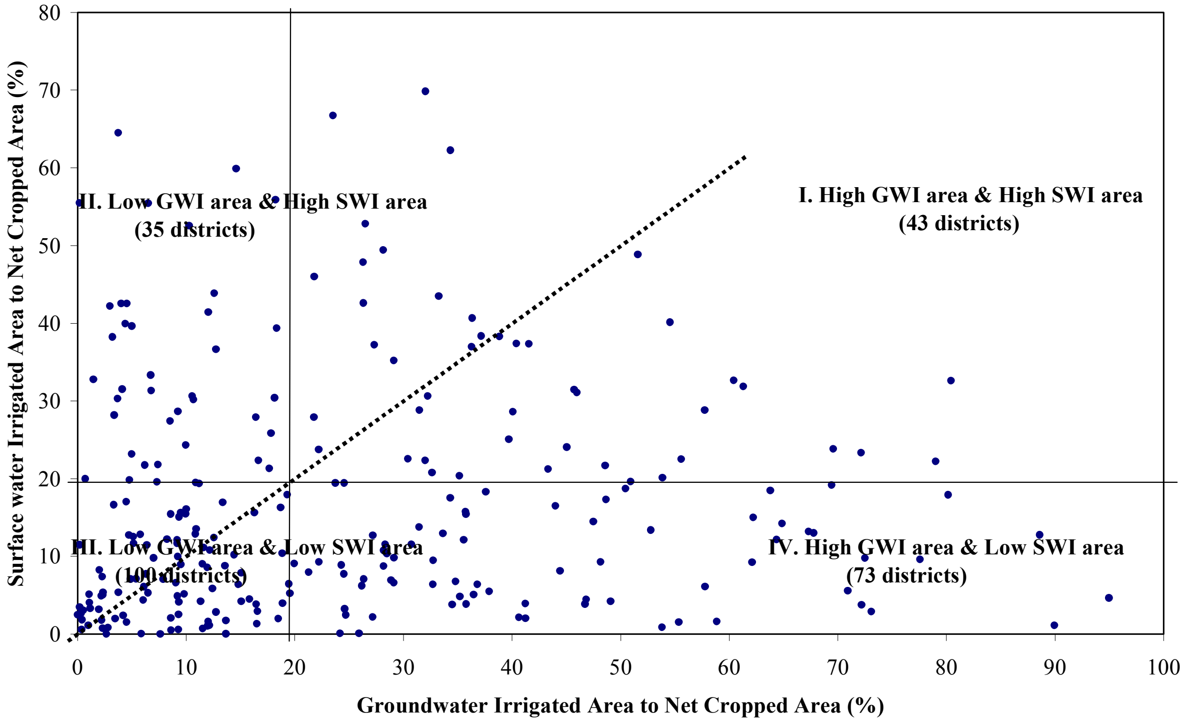


Figure 10.
Groundwater versus surface water irrigation, 1990-93



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 2667 m^3/ha of NCA in 1970, which fell to 2610 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. The following table shows the classification of districts into four categories.

Table 13.
Classification of districts based on area under surface water and groundwater irrigation, 1970-73 and 1990-93

Year	1970-73		1990-93	
Irrigation Category (based on area under groundwater and surface water irrigation to NCA)	No. of districts	% to total	No. of districts	% to total
AA: > 2000 m^3/ ha of NCA and >20% GWI to NCA	39	15.2	86	33.5
AB: > 2000 m^3/ ha of NCA and < 20% GWI to NCA	95	37.0	49	19.0
BA: < 2000 m^3/ ha of NCA > 20% GWI to NCA	7	2.7	37	14.4
BB: < 2000 m^3/ ha of NCA and < 20% GWI to NCA	116	45.1	85	33.1
Total number of districts	257	100.0	257	100.0

Based on source wise irrigation data obtained from ICRISAT (1994) and groundwater data from CGWB, 1995

From the above table it is seen that the number of districts in AA category (both high potential and high use) has gone up from 15.2 percent in 1970 to 33.5 % in 1995, while that in AB category (high potential, low use) has come down from 37.0% to 19.0%. 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 11 and 12 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. It is available on demand, at the 'point of use' needing little transportation, is controlled by the individual farmer. Therefore, productivity from groundwater irrigation is many times larger than surface water irrigation and our models in the previous section support this hypothesis. Groundwater 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 (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.

Figure 11.
Groundwater Availability and Use, 1970

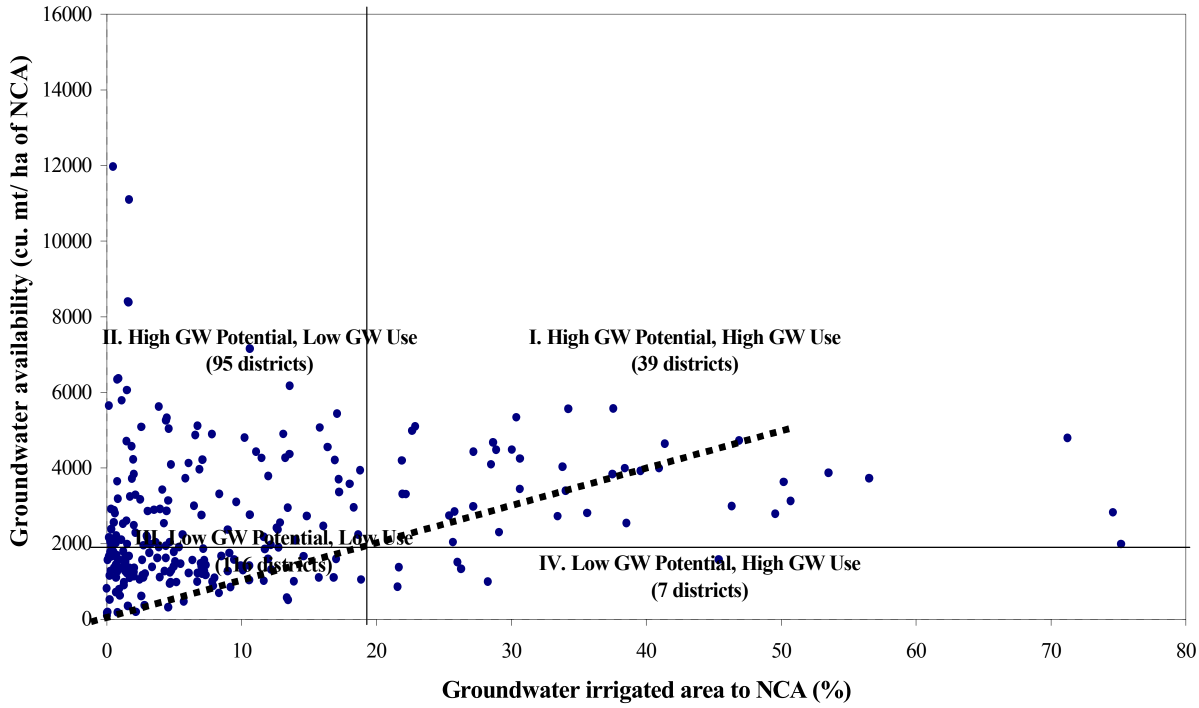
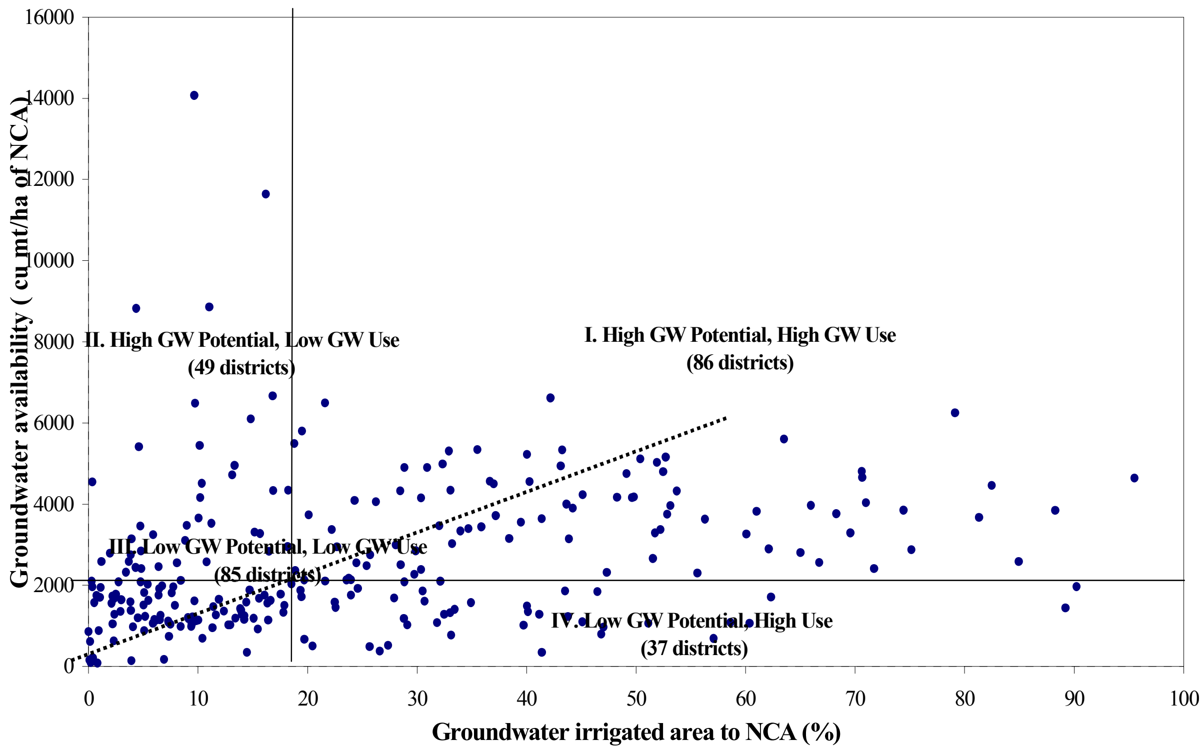


Figure 12.
Groundwater Availability and Use, 1995



The two figures in the page above show that use of groundwater has become more rampant during the 1990's 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 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 unsustainable use and the pathology of decline.

SECTION 4: Socio-ecological fall out of unsustainable groundwater development

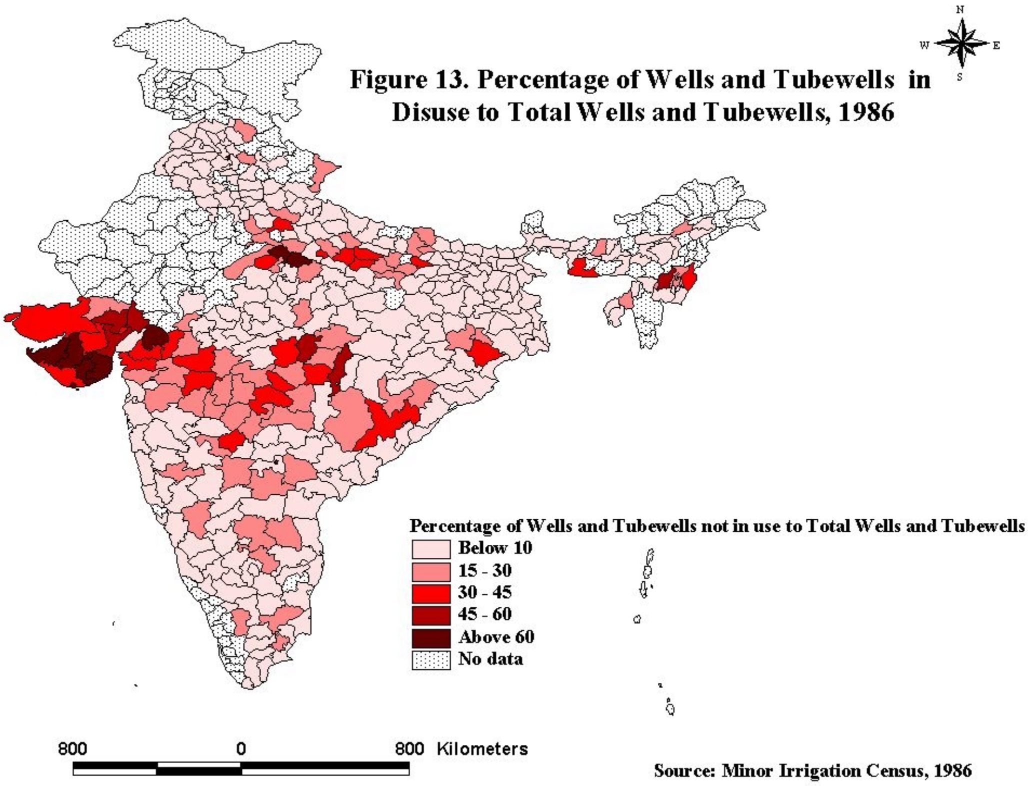
A large part of India's GDP comes from groundwater irrigation. According to the World Bank and Ministry of Water Resources, GOI (1998) estimates, the contribution of ground water to India's GDP is around 9%. The groundwater socio-ecology has been at the heart of India's agrarian boom. However, this booming ground water 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 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 percent per annum, by 2017-18, roughly 36 percent of the blocks in India will face serious problems of over exploitation of groundwater resources.

Table 14. Overexploited and dark blocks in India, 1984-85 and 1992-93

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	253	383

Source: CGWB 1991, 1995

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 13 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.



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 kilometers inland along the coast affecting more than 40,000 well structures (Bhatia, 1992). Similar problems have been recorded in Tamil Nadu's Minjur aquifer. Acquifer 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 (Mudrakartha, 1999).

4.1 The Pathology of Decline

In much of South Asia, for example, the rise and fall of local groundwater economies follow a 4-stage progression outlined in Figure 14 below, 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 14 shows the transition that Indian policymakers and managers need to make from a resource *development* mindset to a resource *management* mode. 40 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 and Levine 1989; Shah, 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 1950's 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 oft 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 groundwater socio-ecology with frightful regularity (Moench 1994; Shah 1993).

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.

4.2 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 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 (Hernandez-Mora et al 1999). 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; [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; [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 and Haddad 1998). Equally instructive for the developing world will be the impact of the entry of big-time corporate players—such as Azurix and the US Filter in the Western US—in the business of using aquifers as inter-year water storage systems for trading of water. As groundwater becomes scarce and costlier to use in relative terms, many ideas—such as trans-basin movement or surface water systems exclusively for recharge--, 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.

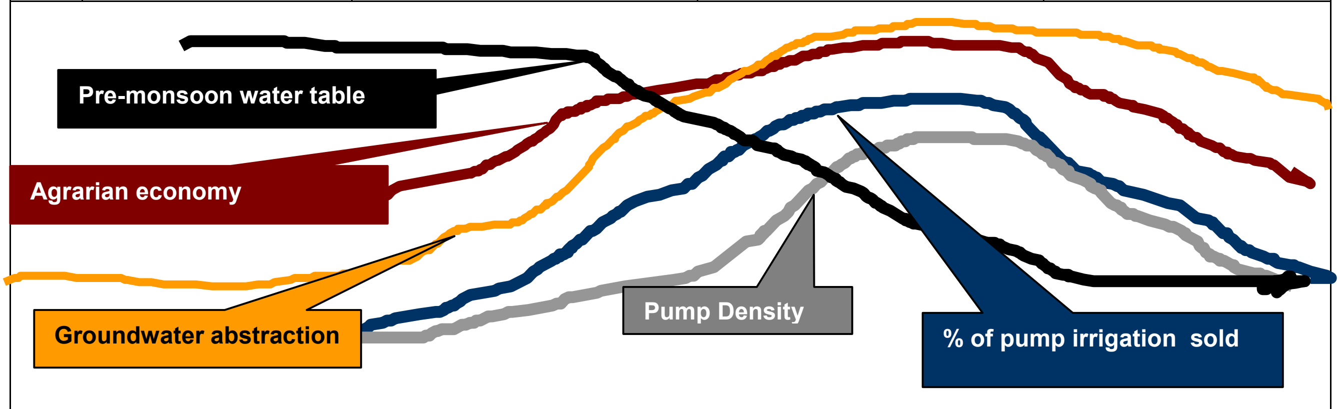
Conclusion and policy implications

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 marginally 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 4.1 percent or Rs 21 billion to total agricultural output in 1970-73. In 1990-93, its contribution has gone to Rs 132 billion or almost 14 percent 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 ground water 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. Overexploitation 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 US 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 South India and North China can not; for instance, what the Netherlands spends per capita on managing its groundwater is 5 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 Asia's groundwater socio-ecology and a resource management approach suited to its genius. In much of Asia, 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. 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 Asia treated water like manna from haven 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, and then offer the foundation on which Asia can build new regimes for sustainable groundwater management.

Figure 14.
Rise and fall of groundwater socio-ecology in India

	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 ground-water 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.

Reference:

Bhatia, Bela. 1992. Lush fields and parched throats: Political economy of groundwater in Gujarat. Working Paper. World Institute for Development Economics Research. Helsinki. Finland.

Bhalla, G.S & Singh G., 2001. *Indian Agriculture: Four Decades of Development.* Sage Publications, New Delhi.

Central Groundwater Board (CGWB). 1991. " Special issue on groundwater statistics". *Bhu-Jal News.* 6(1): 1-162

Central Groundwater Board (CGWB). 1995. *Groundwater resources of India*. Ministry of Water Resources, Government of India. Faridabad.

CMIE. 2000. *Profiles of Districts: October 2000*, Economic Intelligence Service, CMIE, Mumbai.

Dains, S.R & Pawar, J.R. 1987. Economic returns to irrigation in India. Report prepared by SDR Research Groups Inc., for the US Agency for International Development, New Delhi.

Dhawan, B.D. 1982. *Development of tubewell irrigation in India*, Agricole Publishing Academy, New Delhi.

Dhawan, B.D. 1989. Studies in irrigation and water management. Commonwealth Publishers. New Delhi.

Dhawan, B.D. 1995. *Groundwater depletion, land degradation and irrigated agriculture in India.* New Delhi: Commonwealth Publishers

Feitelson, Eran and Marwan Hadda. 1998. Identification of joint management structures for shared acquifers: Cooperative Palestinian-Israeli effort. Unpublished manuscript.

Freeman, D.M., Lowdermilk, M.K., & Early, A.C. 1978. Farm irrigation constraints and farmers responses: comprehensive field survey in Pakistan. Fort Collins, Colorado. Colorado State University.

Government of India. 1992. *All India report on agricultural census, 1985-86.* New Delhi, Ministry of Agriculture.

Government of India. 1986. *Report on Census of Minor Irrigation Schemes-1986-86*, Ministry of Water Resources, Minor Irrigation Division. Government of India, New Delhi.

Hernandez-Mora, Nuria, R. Llamas, L Martinez-Cortina. 1999. Misconceptions in Aquifer Overexploitation Implications for Water Policy in Southern Europe, paper for the 3rd Workshop SAGA, Milan.

Hernandez-Mora, Nuria, L Martinez-Cortina, Juan Mª Fornes Azcoiti. (forthcoming). Intensive groundwater use in Spain. In Llamas R. and Custodio Emilio (eds) *Groundwater Intensive Use: Challenges and Opportunities*. A.A. Blakema Publishers, Rotterdam, The Netherlands.

International Crops Research Institute for the Semi Arid Tropics (ICRISAT). 1994. District level agricultural data. Procured on request in soft copy from Socio-economic policy program (SEPP). Patancheru. India.

Kahnert , F. & Levine, G. 1989. Key findings, recommendations, and summary. Groundwater irrigation and rural poor: Options for development in the Gangetic basin. Washington, DC. World Bank.

Meinzin-Dick, R. 1996. *Groundwater markets in Paksitan: participation and productivity*. Washington. DC. International Food Policy Research Institute.

Moench , M. 1994. Approaches to groundwater management: To control or enable. *Economic and Political Weekly*. September 24: A135: A146.

Mudrakartha, Srinivas. 1999. *Status and Policy Framework of Groundwater in India.* VIKSAT and Nehru Foundation for Development. Ahmedabad. India.

Narain, V. 1998. India's water crisis: avenues for policy and institutional reform. *TERI Information Monitor on Environmental Sceince 2(1):1-6.*

Shah, Tushaar, Alam, M., Dinesh Kumar, M., Nagar, R.K and Singh, Mahendra. 2001. Pedaling out of Poverty: Social impact of a manula irrigation technology in South Asia. Research Report 45, International Water Management Institute. Colombo. Sri Lanka.

Shah, Tushaar. 1993. *Groundwater Markets and Irrigation Development: Political Economy and Practical Policy*. Oxford University Press. Bombay. India.

Shah, Tushaar. 2000. Mobilizing Social Energy against Environmental Challenge: Understanding the Groundwater Recharge Movement in Western India',. Natural Resources Forum, August 2000

World Bank & Government of India. 1998. *India- Water resources management sector review: Groundwater regulation and management report.* Washington D.C., New Delhi, World Bank, Government of India.

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