Groundwater Exploitation in India, Environmental Impacts and Limits to Further Exploitation for Irrigation

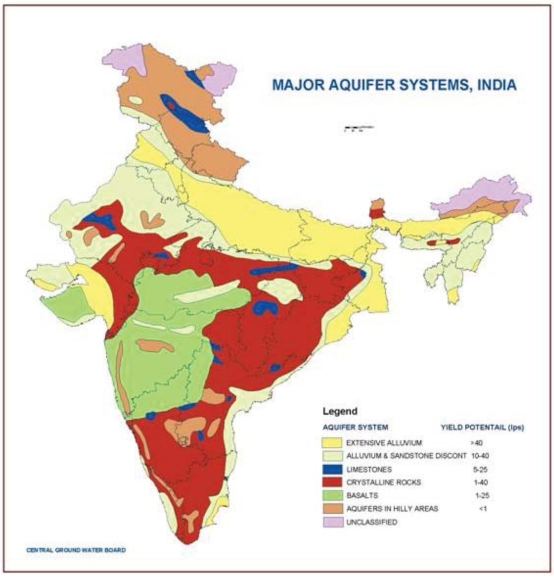
[1]Krishnan Sundarajan, [2]Ankit Patel, Trishikhi Raychoudhury and Chaitali Purohit
[1]Post Doctoral Fellow, IWMI
[2] Consultants, IWMI-TATA Water Policy Program, India

Indian Hydrogeology

We first begin with an analysis of the national level picture following the various hydrogeological zones as provided by previous authors (Karanth 1987; Taylor 1959).

India is divided into 8 provinces for the purpose of the study in groundwater hydrology (Taylor 1959). These are:

Figure 1. Aquifer systems of India.



Precambrian Crystalline Province

This comprises most of peninsular India from the southern tip and ranging up to Delhi. Except for most of Maharashtra state, this mass of Plutonic, Igneous and Metamorphic rocks are of contiguous extant. Groundwater occurs mostly in the weathered zone in the top 10-20 meters, but connection with deeper groundwater is observed at many locations. In most areas, the top weathered zone is underlain by mostly impermeable rock with local or regional fractures yielding storage and transport of water. These entire formations mostly are poor aquifers with low specific yield.

Precambrian Sedimentary Province

Located in 4 distinct regions of the country, these sedimentary formations mainly contain limestone, shale, sandstone, quartzite and local conglomerates. These are located in a) Cuddapah Basin of Andhra Pradesh, b) Raipur Basin of Madhya Pradesh, c) Vindhyan Basin and d) Western Rajasthan Basin. Karstification is observed in varying degrees and some local formations can be sources of springs e.g., as found in Himalayan foothills of Uttaranchal.

Gondwana Sedimentary Province

This province is located in patches of Gujarat, Rajasthan and the coal belt of Eastern India; fluvial or lacustrine consolidated to semi-consolidated shale or sandstone and is generally not highly water bearing. The total thickness of these sediments is up to 6,000 m and can be variable at different locations.

Deccan Trap Province

This is an important province comprising almost the entire state of Maharashtra and parts of others states, e.g., Saurashtra in Gujarat, Western parts of Madhya Pradesh and areas in Karnataka, Rajasthan and Andhra Pradesh. It occupies an area of 500,000 sq. km and consists of volcanic products such as tuffs, breccia, ash and intertrappean basalts. The overall thickness of these flows can be thousand meters or more in some places. Mostly, the water bearing stratum is a top weathered zone up to 50 meters. But at specific locations, the presence of individual horizontal flows can allow large amounts of groundwater storage. The water quality can be brackish especially when overlain by black cotton soils.

Cenezoic Sedimentary Province

This comprises some coastal plains on the Malabar and Coromandel coasts and coastal areas of Kutch and Saurashtra and a region of folded rocks in the far eastern parts of the country. It is underlain by semi-consolidated conglomerates, sandstone, shale and lignite.

Cenezoic Fault Basins

Three fault basins – Narmada, Poorna and Tapi – fall within this province. These contain lenses of sand and gravel along with silt and clay. These are generally good aquifers providing a high yield. The valley fill can range from 50 m to 150 m in thickness. Groundwater quality in the Poorna Basin is highly saline and unfit for irrigation or domestic purposes.

Ganges-Brahmaputra-Indus Alluvial Province

This is the main region of groundwater occurrence in the country with deep high-yielding aquifers and several perennial rivers feeding recharge into these aquifers. Sloping down from the Himalayan foothills, the province can be divided into the a) Bhabhar: high sloping region of the foothills with unsorted sand and gravel offering high infiltration and recharge into lower areas and having deep water table b) Terai: gently sloping region beyond the Bhabhar with tongues of permeable sand, clay and gravel with shallow water table and c) Axial region of deep alluvium comprising sand, gravel and clay aquifers, multi-layered and connected with depth up to several kilometers at some locations.

Himalayan Highland Province

This is a highly folded and faulted zone of mainly sedimentary rocks extending all over the northern region of the country to the far-east. These rocks are mainly limestone, sandstone and shale with some crystalline rocks including granite. Groundwater is characterized by spring in hollows between mountains and intermontane valleys which could have sand and alluvium yielding highly. Some of these intermontane valleys also serve as conduits to recharge the lower plain aquifers.

This sub-division maybe further refined in terms of groundwater provinces.

When comparing statistics of groundwater across the country, the first question that crops up is what is the appropriate unit to be considered? It is common practice amongst different disciplines to use the administrative units for this purpose. But those units are less suitable for assessing groundwater. One option is to refine better this definition of groundwater provinces and consider these units as groups of districts.

In consistency with the division of the country into groundwater provinces, we can classify the country into sub-regions based on these aquifer types. However, the water availability and stress on aquifers also depend on the specific river basin it lies in. For example, the alluvial aquifers of Sabarmati Basin would be much more stressed than those in say, Ganges Basin since the Sabarmati River basin is as a whole a closed river basin. With this in mind, we have divided the country into the major river basins and aquifer types taking a total of 26 river basins or sets of river basins and 7 aquifer zones. This gives a total of 182 sub-regions across the country. Some of these regions are geographic units, for e.g., the Ganges alluvium, the Basalts of Luni which is the Saurashtra basalt block, the Krishna alluvium which corresponds to the delta stretches and so on. This division can provide us with a better unit for the comparison of groundwater use and development that reflects the nature of the aquifer and water availability within the sub-region.

Table 1 shows the total area lying within each of these aquifer-basins (A-B) units. 90 % of the total area comprises 40 of the larger units such as Basaltic Ganges and Cauvery, the Alluvial Indus and Ganges etc. So finally, it is these 40 units which are most important and those, in fact, are expansions of the eight groundwater provinces described earlier. For example, the fourth groundwater province, namely the Ganges-Brahmaputra-Indus Alluvial province is here composed of six smaller A-B units totally comprising 25 % of the area of the country.

Table 1. Area under each aquifer-basin sub-division in India (in 10 MHa).

	Allu_ Sand	Aquifer_ Hills	Basalts	Cryst_ Rocks	Ext_ Alluvium	Limes tone	Un classified	All basins
'Brahm_Bait'	0	0	0	0.3515	0	0	0	0.5339
'Brahmaputra'	0.3461	0.3349	0	0	0.6531	0	0.6204	2.0169
'Cauverg'	0	0	0	0.7587	0	0	0	0.8932
'ERF_Bet_Go_Kr'	0	0	0	0	0	0	0	0.1078
'ERF_Bet_Kr_Pe'	0	0	0	0.1166	0	0	0	0.2297
'ERF_Bet_Ma_Go'	0	0	0	0.3262	0	0	0	0.4333
'ERF_Bet_Pe_Ca'	0.1555	0	0	0.4746	0	0	0	0.6363
'ERF_Sca'	0	0	0	0.2331	0	0	0	0.4237
'Ganga'	1.7143	0.7042	0.5985	1.7721	3.6093	0.2148	0	8.6161
'Godavari'	0.1504	0.1227	1.5201	1.3258	0	0	0	3.1965
'Indus'	1.5332	1.0896	0	0.1292	0.261	0.3118	0.1559	3.4807
'Krishna'	0	0.3249	1.2242	0.7996	0	0	0	2.4965
'Luni'	0.9311	0.1079	0.4011	0.314	0.3373	0	0	2.2092
'Mahanadi'	0.1865	0	0	1.0866	0	0.1253	0	1.4904
'Mahi'	0	0	0	0.2606	0	0	0	0.3727
'Meghna'	0.4375	0	0	0	0	0	0	0.4725
'Narmada'	0.1904	0	0.5642	0.2298	0	0	0	1.0312
'No Data'	0	0	0	0	0	0	0	0.0366
'North Ladakh'	0	0.1543	0	0	0	0	0	0.2513
'Pennar'	0	01.98	0	0.2928	0	0	0	0.5466
'Rivers_Bangaladesh'	0	0	0	0	0	0	0	0.0261
'Rivers_Myanmar'	0.2462	0	0	0	0	0	0	0.3165
'Sabarmati'	0	0	0	0.1221	0.1135	0	0	0.2643
'Subarnarekha'	0	0	0	0.1591	0.1081	0	0	0.3479
'Tapi'	0	0	0.4635	0	0	0	0	0.6292
'WRF'	0.1577	0.1857	0.2455	0.3766	0	0	0	0.9856
All aquifers	6.8151	3.4299	5.096	9.2891	5.5633	0.9275	0.9238	32.0447

Note: 0 = relatively negligible area

A note on the Luni River is required. According to the classification made here, the Luni River basin comprises all the west flowing rivers through Kutch and Saurashtra lumped together. This would include rivers such as Gehlo in Saurashtra and Banas in North Gujarat also.

Since the national-level data are available on a district-wise basis, we have classified the districts of the country into the specific aquifer and river basin they fall into. In case of a single district lying in multiple aquifer type and river basin, we have taken the proportion of each unit within the district. This allows us to assign each district into one or more of these aquifer-basin sub-regions and the proportion of the district falling into each of these sub-regions.

National Picture of the Current Level of Groundwater Exploitation

Exploitation of groundwater resources has been occurring across India for various reasons, irrigation being prime among them. The level of exploitation, however, is not the same across different regions. Recent information provided by the CGWB (CGWB 2005) with revised methodology for estimating groundwater availability and withdrawal provided more accurate means of determining this spatial variation in level of groundwater exploitation.

Table 2. Average level of groundwater development within each aquifer-basin subdivision of India.

	Allu_ Sand	Aquifer_ Hills	Basalts	Cryst_ Rocks	Ext_ Alluvium	Limes tone	Un classified	All basins
'Brahm_Bait'	0	0	0	31.14292	0	0	0	34.601
'Brahmaputra'	26.95509	28.03682	0	0	29.36169	0	19.09301	25.946
'Cauverg'	0	0	0	71.77566	0	0	0	68.218
'ERF_Bet_Go_Kr'	0	0	0	0	0	0	0	43.265
'ERF_Bet_Kr_Pe'	0	0	0	46.48832	0	0	0	45.775
'ERF_Bet_Ma_Go'	0	0	0	33.23786	0	0	0	35.206
'ERF_Bet_Pe_Ca'	45.618.06	0	0	82.18662	0	0	0	72.884
'ERF_Sca'	0	0	0	51.57819	0	0	0	49.417
'Ganga'	69.63594	61.53064	68.33573	57.67545	58.79498	43.99457	0	61.234
'Godavari'	42.7542	46.84313	49.71349	29.2406	0	0	0	40.614
'Indus'	92.2491	38.23346	0	65.07784	86.51055	53.1461	44.79518	68.274
'Krishna'	0	50.71128	60.33734	50.75385	0	0	0	54.959
'Luni'	96.53928	62.00874	56.44425	92.62885	65.61803	0	0	80.339
'Mahanadi'	39.15397	0	0	29.64438	0	42.68911	0	32.523
'Mahi'	0	0	0	54.08463	0	0	0	54.232
'Meghna'	24.90399	0	0	0	0	0	0	26.228
'Narmada'	41.38124	0	49.01113	44.35889	0	0	0	46.387
'No Data'	0	0	0	0	0	0	0	0.000
'North Ladakh'	0	44.79518	0	0	0	0	0	0.000
'Pennar'	0	54.44892	0	61.68887	0	0	0	57.423
'Rivers_Bangaladesh'	0	0	0	0	0	0	0	42.274
'Rivers_Myanmar'	32.55187	0	0	0	0	0	0	33.985
'Sabarmati'	0	0	0	56.85779	57.33358	0	0	55.864
'Subarnarekha'	0	0	0	36.1618	42.56311	0	0	39.261
'Tapi'	0	0	52.28134	0	0	0	0	50.461
'WRF'	45.02918	43.70353	41.34749	42.66015	0	0	0	42.952
All aquifers	65.686	46.371	54.714	49.816	55.305	48.644	27.848	53.880

Lacunae in Estimation Procedure

There are however still lacunae in this estimation procedure and many of the deficiencies shown by authors (Dhawan 1990; Shah et al. 1998) still persist. Inconsistencies between different sources of data provided by government data collection agencies have been reported by various authors. The estimation of total groundwater use can be performed using different means: a) a direction estimation through volumetric changes in groundwater storage and b) indirectly through accounting for different uses such as area irrigated by groundwater. Dhawan points out that there are high differences between these estimates partly due to the procedures adopted by the agencies in the estimation procedures. The volumetric procedure of the Central Groundwater Board (CGWB) takes as unit blocks or Talukas and in some states such as Maharashtra, the unit is a watershed. An entire water budgeting is performed for this unit in terms of recharge, use for various purposes and discharge. However, estimates of discharge such as to streams are questionable since the data available for such estimation are not reliable. The estimates too have been changing over the years and in general, been observing a greater degree of exploitation of resources with each survey. Another important factor is regarding the density of the monitoring network and how informative it is for computing the change in groundwater storage. Especially, in the hard rock area such estimation can be highly unreliable and can be compounded by poor data on specific yield of unconfined aquifers.

On the other hand, the Planning Commission’s estimate of area irrigated by groundwater and potential irrigable area show a different picture (Dhawan 1995). As pointed out by Dhawan, there has been full exploitation of groundwater resources on the country as a whole in early 1990s and overexploitation in Uttar Pradesh and Gujarat, whereas the then CGWB estimates showed only 30 % exploitation on the country as a whole. One striking example of inconsistencies provided by different data is the situation in Punjab. Whereas volumetric estimates of groundwater balance show a rise in water table, the groundwater level data show a fall in water table for the Sirhind Canal tract (Dhawan 1995).

These notwithstanding, the CGWB estimates of 2004 provide the only picture of groundwater in India which is closest to the reality. The deficiencies are being improved upon and would probably get closer to the true picture with further surveys.

In general, the level of exploitation in many aquifers still shows numbers on the lower side, i.e., being optimistic about available reserves.

Observations from CGWB 2004 Data

The current CGWB methodology follows revised norms using the GES 1997 Estimation methodology (GEC 1997). Under this methodology, the level of groundwater development in a unit of study (Taluka, block or watershed) is defined as:

- Stage of Groundwater Development = Annual Groundwater draft/Net Annual Groundwater availability * 100

This definition adopted by CGWB has however been contested by some authors (Shah et al. 1998), who propose the denominator to be the ‘utilizable’ groundwater as opposed to ‘available groundwater’ reserves. In the estimates by Shah et al. the stage of groundwater development is as large as two to three times the CGWB estimates when using their proposed definition. However, these estimates are using previous data of 1990 and data prior to that. It remains to be seen how the present estimates would modify under such a proposed change in the definition of groundwater development.

The assessment of these units by CGWB into safe, semi-critical, critical and over-exploited is based on two criteria: a) The stage of groundwater development and b) long-term trends of pre and post monsoon groundwater levels within that unit. As far as possible, a minimum data of 10-year duration is used for this analysis. Water level decline is defined as being significant if it is at least 10 cm to 20 cm per year depending on the specific hydrogeological conditions of that unit.

Table 3. Categorization units into levels of criticality of groundwater development.

	Stage of GW development	Significant long-term decline		Categorization
		Pre-monsoon	Post-monsoon	
1	<= 70 %	No	No	Safe
2	> 70 % and <=90 %	No	No	Safe
		Yes/No	No/Yes	Semi-critical
3	> 90 % and <=100 %	Yes/No	No/Yes	Semi-critical
		Yes	Yes	Critical
4	> 100 %	Yes/No	No/Yes	Overexploited
		Yes	Yes	Overexploited

A summary of this entire categorization of 5,723 units across the country shows that 71 % are safe, 10 % are semi-critical, 4 % are critical and 15 % are over-exploited. This shows wide variation across the hydrogeological zones of the country. For example, Bihar state that lies entirely within the Gangetic-Alluvial sub-region has 100 % units classified in the safe category. On the western side of the Indus-Alluvial region in Punjab, however, we see that 75 % units are over-exploited. Gujarat, Haryana, Karnataka, Tamil Nadu, Rajasthan and Andhra Pradesh are other states with a high percentage of over-exploited units.

Within each sub-region we compute the average level of groundwater development using the individual statistics of water availability and use. The summary from this analysis is shown in Table 2.

The highest levels of development are shown by Luni-Alluvial Sand of 96 %. This is composed of the Rajasthan districts such as Barmer, Pali and Sirohi and Gujarat districts such as Amreli, Banaskantha, Junagadh, Kutch and Bhavnagar. These are regions of very low rainfall (annual average < 500 mm), high coefficient of variation in annual rainfall and almost no canal irrigation systems on a regional scale. Also, they are affected by a range of water quality problems such as Salinity, Fluoride etc.

The Luni-Crystalline region has a level of groundwater development of 92 %. This is mainly the Aravalli crystalline rock region where there is poor recharge of groundwater in spite of reasonable rainfall (700mm-1,300mm). There is a high failure rate of wells and a high cost involved in the deepening of wells. Overall the Luni River basin has a level of groundwater development of 80 %.

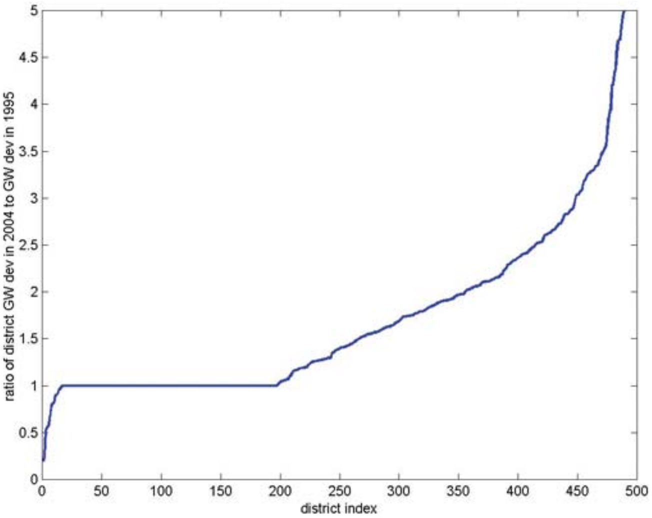
Next, the Indus Basin alluvial sand and extensive alluvial region shows a high level of groundwater development of 92 % and 86 % respectively. This includes the heavily canal and groundwater irrigated areas of Punjab and Haryana which are the areas of intensive agriculture. Many of these areas have witnessed a fall in water tables for the past decade. Highly exploited districts are Jalandhar, Patiala, Sangrur, Amritsar, Bathinda and Ludhiana in Punjab and Karnal, Kurukshetra and Kaithal districts in Haryana and Barmer, Jaisalmer, Nagaur and Sikar districts of Rajasthan. The high level of groundwater exploitation in these areas has reflected in secular fall in water tables and worsening water quality. The problem of high Fluoride levels (> 1 mg/l) in deeper groundwater is a severe problem in the western and southern districts of Rajasthan (Chaubisa 2001).

Next in high level of groundwater development of 82 % is the Crystalline hard rock area between Pennar and Cauvery river basins comprising the coastal Tamil Nadu districts of Cuddalore, Kancheepuram, Pondicherry and parts of Bangalore and Chitoor. Many of these coastal areas suffer from quality problems due to coastal saline intrusion as well as inherent salinity in groundwater.

The Cauvery crystalline region is another large area with a high level of exploitation of 72 % comprising large areas of Tamil Nadu and Karnataka states. This region especially assumes importance since the Cauvery Basin itself is highly stressed resulting in issues of water sharing. This is only compounded by the high level of groundwater exploitation that reflects in increasing fluctuations of water table across seasons.

The Basaltic part of Krishna Basin is another highly exploited region with 60 % exploitation. This mainly comprises districts in Maharashtra, Karnataka and Andhra Pradesh.

Figure 2. Ratio of the level of groundwater (GW) development of districts in 2004 to that in 1995 (arranged in increasing order of the ratio).



The increase in level of GW development from 1995 statistics to 2004 statistics.

Ratio of GW development from 1995-2004	No. of districts
0-1	20
1-2	330
2-3	100
3-4	25
4-5	25

The previous CGWB groundwater statistics were brought out in 1995. Since then, there has been a revision in methodology of groundwater computation (GEC 1997). The revision in methodology corrects some of the lacunae mentioned earlier and it is expected that a more correct picture is now reflected in the current methodology. When the 2004 levels of groundwater development are compared with the 1995 levels, (Figure 2, the districts have been arranged in increasing order of ratio of 2004 to 1995 levels of GW development), we see that very few districts (less than 20) show a decrease in levels of GW development. Most show the same or an increase in levels of GW development from before with some showing as much as a 5 time increase. Note that this reflects a change in methodology as well as fresh data from the past decade. The introduction of HLDR piezometers in the peninsular states under the Hydrology project also has an impact.

Environmental Impacts of Overexploitation

Nevertheless, a comparison across the country offers us a possibility of comparing across the same bias (assuming similar errors due to this methodology). These figures should be taken along with observations of local adverse impacts on the environment such as falling water tables, high seasonal fluctuations in water tables, deteriorating water quality, land subsidence – all of which together provide us with a picture of groundwater exploitation.

We first start from the Himalayan region where groundwater exploitation has not been very high, but has been showing pockets of disturbance in the past decade. Most rural areas in the mountains and towns in this region depend on spring water for their domestic and other uses. In the past, such use of spring water was not exploited on a large scale, but is now widespread and therefore leading to overexploitation. One example is that of the Almora Town (Kumar and Rawat 1996). Spring water is essentially groundwater that is discharged at points where the piezometric surface intersects the ground level. Therefore, the discharge of springs is closely related to exploitation of groundwater and development activities in recharge areas of the springs. The major problem with such springs in mountain towns such as Almora is the pollution levels due to inadequate protection. This when combined with increasing use cause lowering of discharge and poor water quality. Fast developing areas in the Himalayan region such as the Doon Valley face critical problems of groundwater exploitation (Bartarya 1997). Such valleys are composed of rich intermontane alluvial aquifers recharged by the springs originating in surrounding hills, in this case the Mussourie Hill region. However, there is a combined effect of the springs being diverted for other uses and high overdraft in the valley region that results in depleting groundwater levels in the Doon Valley.

The Siwalik and foothill region of the Himalayas are characterized by typical groundwater problems. The Kandi region spanning from Kashmir region, Punjab and Haryana is the transitional zone between the Siwaliks and the plains (Shardha and Bagchi 2001). Deep groundwater tables, high speed of groundwater flow, uncertain composition of aquifers and some challenges associated with the groundwater use in this area. In such areas, even any moderate development of groundwater results in high levels of exploitation.

In the Himalayan region more than in any other place, the impact of groundwater development on interaction between surface and groundwater is clearly visible. Springs are one example of this interaction. Lack of protection of recharge areas has led to drying up of a large number of such mountain springs all across the Himalayan region (Valdiya and Bartarya 1989). But this is visible in the lean season flows of the Himalayan rivers for which much of the non-monsoon flows are fed by base flow components from contributing catchments. The effluent nature of Doon Valley aquifer into the Son River is one example. Ongoing research is looking at this magnitude of base flow contribution and its variation with high groundwater development in the catchment areas.

The Indus-Gangetic Alluvial plains from Punjab up to West Bengal form the main groundwater occurring region of the country. There is a vast variation, however, in the aquifer structures, availability of groundwater and groundwater quality across this region. The Punjab plains have in the past 3-4 decades witnessed a boom in groundwater use and many authors have studied this problem of depleting water quality and fall in water tables (Dhawan 1995; Sondhi et al. 2001; Ambast et al. 2006). Many districts of Punjab show 100 % or greater levels of exploitation which is exhibited by a secular decline in pre-monsoon water tables except for extremely wet years. The Bist-Doab tract lying between the Beas and Sutlej rivers consists of several districts that have now local aquifers with an annual decline of more than a meter in phreatic water levels. The problem with authenticating these facts with scientific observation lies in the poor quality of data referred to earlier. Most water level data sets collected by agencies are fraught with missing data, inconsistent information and lack of agreement with local ‘common sense’. An analysis of pre-monsoon water level data of Bist-Doab area of 33 monitoring wells show 22 % of missing data in the data set.

The central and eastern parts of the Indus-Gangetic Plains have in general a problem of economic access to groundwater rather than actual physical scarcity. In these regions with poor rural electricity, a marginal rise in diesel prices or a few meters fall in water table results in groundwater irrigation becoming economically unfeasible for many crops and small landholders. Therefore, even a 50-60 % level of current groundwater exploitation in many of these eastern areas can cause difficult access to groundwater.

The alluvial aquifers of North Gujarat are another zone of high groundwater exploitation (Kumar and Singh 2007). In the highly overexploited Mehsana aquifer, water tables have been falling at rates of more than a meter every year and currently the 5th or 6th aquifer is being used by wells that are the deepest ones in the country. Spurred by the dairy industry and high water yielding crops, this region has witnessed one of the extreme cases of groundwater overuse. This exploitation has also led to quality problems in water, especially high levels of Fluoride (Gupta et al. 2005) as a result of exploiting water of high residence time (> 1,000 years) that has led to excessive mineralization.

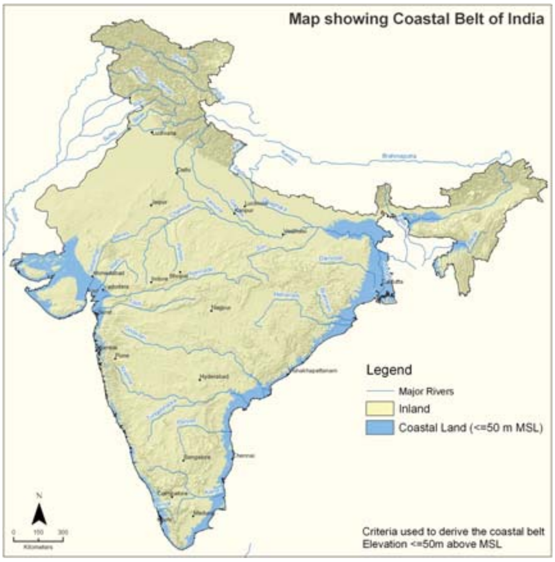
Crystalline aquifers of Tamil Nadu show a high degree of groundwater exploitation since the past 2-3 decades. The Noyyal River basin, a sub-basin of Cauvery, is a representative example of typical problems facing other areas of the state (Mayilsami et al. 2007). Increasing fluctuation of water levels in wells and secular decline has lead to high failure rate in this area. The percentage of open wells dried up was 48.68 % compared to borewells 9.99 %.

Due to low specific yield, most of the hard rock regions in peninsular India have very less water bearing capacity, therefore overexploitation of groundwater reflects high fluctuations in water levels across seasons within a year. A typical stratum in hard rock terrain comprises a top soil of few cms to a meter thick followed by top weathered zones of few meters depth followed by the base rock. Due to this, competitive well deepening has led to elimination of shallow wells from the groundwater irrigation scene (Janakarajan 1999). This also increases well failure that can be as high as 50 % (Mayilsami et al. 2007). The cost of additional wells and deepening cost associated with well failure can be as high as Rs. 22,000/year (NIH 1999).

Impacts on Groundwater Quality Due to Overexploitation

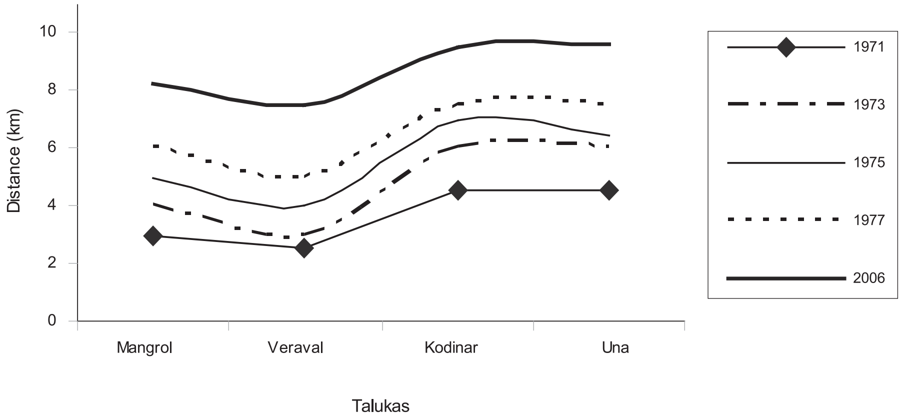
Another level of constraint on further expansion of groundwater based irrigation is the quality of groundwater. Both inland and coastal salinity together impose restrictions on the expansion of irrigation in some areas. Pockets of coastal areas are experiencing seasonal and long term trends of inland migration of high saline water due to various reasons – increased pumping, decrease in river flow, coastal aquaculture, and tidal effects. A combination of these along with geologic and geomorphic factors cause the variable salinity along the Indian coast. We view the salinity aspect as another constraint in this picture of groundwater based irrigation.

Figure 3. Coastal zone across India.



Salinity in coastal region is a widespread problem in the entire coast in the world. In order to increase the productivity of sustainable fresh water from the coast, proper mechanism of salinity should be understood thoroughly. Those need extensive study and research on meteorology, geomorphology and geology of the area. Coastal India can be divided into mainly four physiographical divisions. East coast plain, west coast plain, Gujarat plain and Indian islands are those major divisions. The East coast deltas of major rivers like Ganga, Mahanadi, Krishna, Cauveri, and Godavari are affected by salinity much more compared with the hard-rock region. Intensity and mechanism of salinity in those deltas also differs depending upon their soil composition and meteorology. On the other hand, in the west coast mainly Kerala is affected by salinity due to inland movement of sea water through creeks. Gujarat coastal area is a most severely salinity affected region by combined effects of all the scenario mentioned above. And its geomorphology and meteorology are favorable to salinity. The West Bengal coastal area mainly faces tidal effects and inherent salinity.

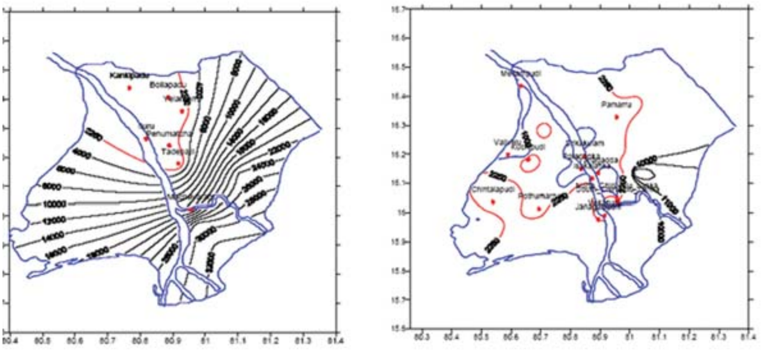
Figure 4. Salinity ingress profile in Junagadh, Gujarat from 1971 till 2004.



Junagadh coastal area is one of the salinity affected areas mainly due to sea-water intrusion during last two-three decades. In the mid 1950s, introduction of pumping technologies in the area made the agriculture production very high. As a result in the 1960s, the withdrawal rate of groundwater became 10 to 25 times more than that of previous decade. This extensive pumping caused unbalance in recharge and withdrawal phenomenon that resulted in sea-water intrusion. Figure 4 shows the salinity ingress profile in 2006 is within 7.5 km to 9.5 km inland on the average while in 1977 it was observed within 5 km to 7.5 km. Since the past two decades, there have been several interventions in the form of tidal regulators and watershed activities in this area, but they have not been significantly effective in reducing the rate of ingress.

The Krishna delta area of Andhra Pradesh is another region that has been observing an increase in coastal salinity of groundwater. Here though, the cause of salinity increase is not exactly ingress of saline water, but the reduction in early season river flows from the Krishna River. It is observed that the pre-monsoon freshwater-saline water interface has moved inward and upward by 5m to 8m from 1976 studies. This occurrence is expected due to the effect of reduction in Krishna River flow and the extensive spread of aquaculture in this area (APSGWD 2003).

Figure 5. Salinity profile in Krishna delta (migration of 2,200 EC contour inwards).



Post monsoon 1976

Post monsoon 2002

On the other hand, the Bengal delta area faces the problem of tidal water ingress during high tides over all salinity in coastal Bengal and this can be explained by three main mechanisms: i) over pumping of groundwater at upstream cause's saline groundwater to flow further inland and the sea-water intrusion in confined aquifer takes place. ii) as this delta is a low marshy land, the creeks and the aquiculture ponds are extended far in inland. At the summer or pre monsoon period these creeks and aquiculture ponds get filled up with saline water. As the groundwater extraction takes place the saline water reaches the ground water by upcoming mechanism. iii) as the soil moisture content decreases largely in summer, the saline groundwater from shallower water table rises due to capillary action. These are the main micro-scale mechanism which act combined as the causes in macro-scale salinity problem.

Impacts on Growth in Groundwater Based Irrigation

There are various degrees of dependence of Indian agriculture on groundwater. Some authors quote a number as high as 75 % (Debroy and Shah 2003) whereas others quote numbers like 65 %. Nevertheless, groundwater based irrigation fed either by natural recharge or by canal fed recharge has gained increasing importance in Indian agriculture. This has however come at a cost. The high levels of groundwater exploitation across the country impose constraints on further growth in groundwater based irrigation. We proceed for this analysis in a similar form as previously with the aquifer-basin units. As can be seen from this table, the hard rock areas, though large in surface area, do not contribute as much to the groundwater irrigated areas.

Table 4 shows the gross groundwater irrigated areas within each A-B unit across the country according to the 2001 census of Agricultural Statistics (GOI 2001). The alluvial regions of the Ganges are the greatest contributor to groundwater based irrigation. In all, the alluvial regions contribute 65 % of the total groundwater irrigated area in the country whereas they comprise only 38 % of the extent of the country.

The CGWB 2004 groundwater statistics also provides as an estimate the amount of replenishable groundwater available for future use. Of course, for districts where groundwater is overextracted, this amount would be negative. The 1995 CGWB groundwater statistics also

Table 4. Gross groundwater irrigated area (MHa) in 2001.

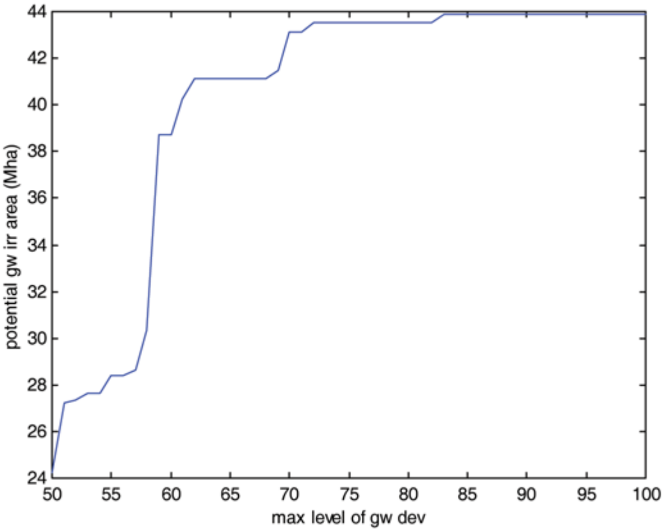
	Allu_ Sand	Aquifer_ Hills	Basalts	Cryst_ Rocks	Ext_ Alluvium	Limes tone	Un classified	All basins
'Brahm_Bait'	0	0	0	0.1114	0	0	0	0.1344
'Brahmaputra'	0.0857	0.2161	0	0	0.1397	0	0.3622	0.8072
'Cauverg'	0	0	0	0.2996	0	0	0	0.3462
'ERF_Bet_Go_Kr'	0	0	0	0	0	0	0	0.0219
'ERF_Bet_Kr_Pe'	0	0	0	0.0502	0	0	0	0.1002
'ERF_Bet_Ma_Go'	0	0	0	0.0562	0	0	0	0.0808
'ERF_Bet_Pe_Ca'	0.0604	0	0	0.478	0	0	0	0.5424
'ERF_Sca'	0	0	0	0.1713	0	0	0	0.2905
'Ganga'	3.0148	0.58	0.4887	1.116	10.074	0.1002	0	15.3769
'Godavari'	0.1614	0.1031	1.0545	0.3417	0	0	0	1.6981
'Indus'	1.9711	0.1254	0	0.0372	1.3961	0.012	0	3.5418
'Krishna'	0	0.1845	0.9697	0.3786	0	0	0	1.619
'Luni'	0.8804	0.0982	0.555	0.4293	0.4234	0	0	2.4345
'Mahanadi'	0.0203	0	0	0.1829	0	0.0408	0	0.261
'Mahi'	0	0	0	0.1462	0	0	0	0.2021
'Meghna'	0.0118	0	0	0	0	0	0	0.0119
'Narmada'	0.2538	0	0.2575	0.0722	0	0	0	0.603
'No Data'	0	0	0	0	0	0	0	0.0002
'North Ladakh'	0	0	0	0	0	0	0	0
'Pennar'	0	0.1047	0	0.1806	0	0	0	0.3203
'Rivers_Bangaladesh'	0	0	0	0	0	0	0	0
'Rivers_Myanmar'	0.158	0	0	0	0	0	0	0.1595
'Sabarmati'	0	0	0	0.3184	0.2588	0	0	0.6167
'Subarnarekha'	0	0	0	0.0114	0.0526	0	0	0.0792
'Tapi'	0	0	0.331	0	0	0	0	0.4136
'WRF'	0.0346	0.0535	0.0437	0.2296	0	0	0	0.3762
All aquifers	6.9222	1.6122	3.7303	4.6225	12.4656	0.3051	0.3797	30.0376

Source: Agricultural statistics 2001

provided along with this estimate, the total gross area irrigable through groundwater in that district. This was done by using the 'delta' figure i.e., the average depth of consumptive water use for crops in that district. This number is derived from surveys of agricultural census. Here, these estimates of delta and available groundwater are used to arrive at the maximum potential irrigable area using groundwater.

However, this potential area can be constrained due to overexploitation. Therefore, we have considered the maximum levels of groundwater development to be a limiting quantity, say 65 % and only calculated the potential irrigable areas for all those districts below this level of development. This can be done for any proposed maximum level of development, say

Figure 6. Possible incremental groundwater irrigated area with different groundwater development constraints.



from 50 % till 100 %. For each level of maximum groundwater development, we can obtain a potential irrigable area using groundwater. Figure 6 shows these estimates for maximum level of groundwater development from 50 % till 100 %.

All these impose a limit on the growth of groundwater based irrigation – which remains as the largest user of groundwater. Groundwater based irrigation also has limits imposed on it by a combination of different factors: arable land, availability and economic access to energy, capital for investment on well technology. These factors are exacerbated by the depletion in groundwater availability. Some figures provided by irrigation and agriculture statistics give us an indication of the trend in the area irrigated by groundwater (but not the exact areas due to associated errors) and how this could behave in the future due to constraints imposed by resource availability.

Urban Growth and Groundwater Exploitation

Urban areas increasingly present zones of future groundwater exploitation and possible competitors to groundwater for irrigation. This competition between urban and agricultural use for groundwater happens in different ways – directly i.e., groundwater from urban areas is supplied from peri-urban areas (Phansalkar et al. 2005; Londhe et al. 2004) and indirectly wherein diversion of reservoir water to thirsty cities results in greater dependence of irrigation on groundwater.

Several trends emerge when one considers the urban towns across the country in terms of their groundwater use. First it is seen that aquifer type is an important factor in deciding how much the city depends on its local groundwater for overall water use. Table 5 shows that the level of dependence on urban areas on groundwater is much greater in the Alluvial aquifer areas with assured water supply as compared with the Basaltic and Crystalline hard rock areas.

Figure 7. 300 urban areas of India over river basins and aquifer types.

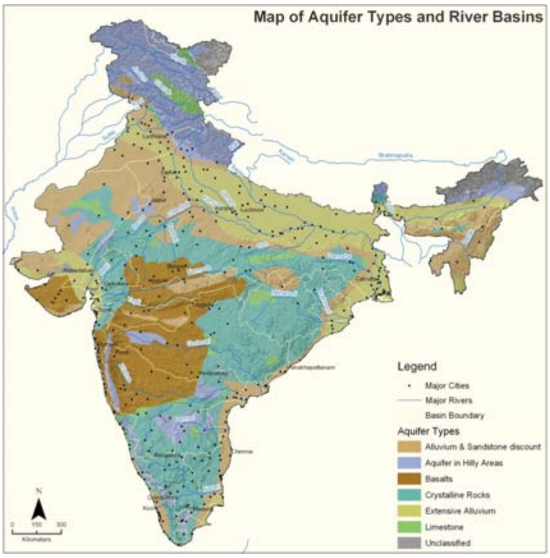


Table 5. Groundwater dependence of urban areas for each aquifer type.

Aquifers	No. of towns	Dependance on local groundwater
Alluvium and sandstone discourse	78	44 %
Aquifer in hilly areas	19	47 %
Basalt	43	8 %
Crystalline rocks	70	21 %
Extensive alluvium	84	75 %
Limestone	2	5 %
Total	296	42 %

This dependence on local groundwater also varies across the size of cities in terms of population. It is seen that in general, smaller towns have lesser ability to attract water from far away sources, hence more dependant on local groundwater. Table 6 shows that across class sizes, the average dependence of an urban area on groundwater increases from 12 % for the metropolitan cities to 36 % and 49 % for Class I and Class II cities.

When we compare the level of groundwater development in a basin along with the dependence of urban areas within that basin for groundwater, a picture of overall stress within that basin can be obtained (Table 7). Basins where there is already a high level of groundwater development and urban areas depending upon surface water more for their needs, one would see greater competition between urban and other uses for basin water resources in the future e.g., Krishna and Sabarmati basins.

Table 6. Groundwater dependence of urban areas for each city class type.

Size class of urban centers	%Water drawn from	
	Surface source	Ground source
Metropolitan cities	88	12
Class I cities	64	36
Class II towns	52	49
Total no. of cities/towns	78	22

Table 7. Groundwater dependence of urban areas within each basin.

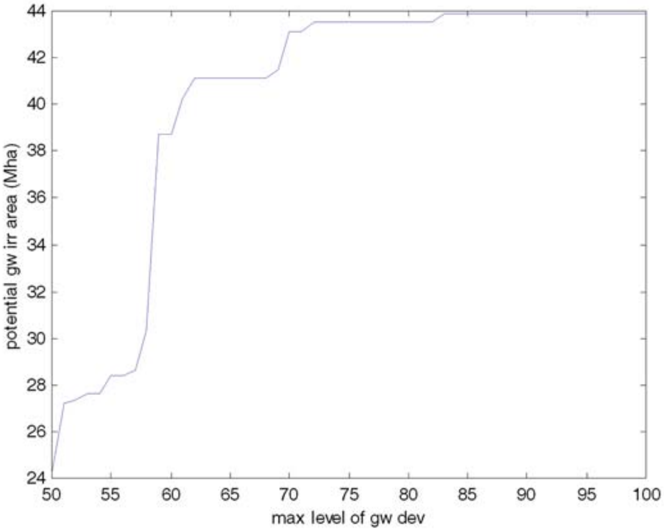
Basin	No. of towns	Average level of GW dev	Average % of GW supply in cities
Barak	5		11.34
Brahmani_Baitarn	3	34.6	66.67
Brahmaputra	5	25.9	21.82
Cauvery	17	68.2	7.35
ERF1	7	44	22.02
ERF2	18	61	22.20
Ganga	109	61.2	66.94
Godawari	18	40.6	5.37
Indus	21	68.27	66.46
Krishna	26	54.9	14.39
Luni	16	80.33	35.83
Mahanadi	5	32.523	27.55
Mahi	4	54.232	50.74
Narmada	5	46.387	28.21
Pennar	8	57.42	47.62
Sabarmati	3	55.86	40.93
Tapi	5	50.46	0.00
WRF	21	42.95	19.05
Total	296	53.88	41.10

Succinctly, fast growing and emerging urban centers are demanding water to achieve higher growth rates. There is a strong spatial variation in the dependence on groundwater of the towns and cities. The peninsular and primarily hard rock cities show high dependence (average more than 80 %) on external sources of water, whereas, the alluvial aquifer cities are more dependant on local groundwater (average 75 %). The size of a city is also a strong indicator of how much surface water it can import. As the city-size grows the dependence on imported water increases and though smaller towns are witnessing rapid growth, they have to increasingly rely on local water supplies. In the regions where groundwater over-development has already occurred, cities are competing with irrigators for water. Hence, urban development can hinder the growth of agriculture in neighboring areas, where prevailing characteristics i.e., size of the city, aquifer conditions and present groundwater development force urban areas to import surface water. In the context of possible interbasin water transfers, these water-starved urban centers could attract the arriving water on priority basis.

Conceptualizing All Constraints on Groundwater Based Irrigation

A combined picture of all these factors give us a scenario in which the growth of groundwater based irrigation can be thought about. These environmental constraints and urban requirements are identified here as the major factors. These together give us a picture of comparing across river basins and aquifers and projecting as to what use additional water entering these regions would be put to.

Figure 8. Possible incremental groundwater irrigated area with multiple constraints.



This is a conceptual picture that needs to be strengthened by further studies on each of these issues. Many areas that have much potential in groundwater development, e.g., parts of Bihar and West Bengal, are limited by the availability of land and also affected by an energy crisis of pumping groundwater. Overall, it is clear that there are very few areas where growth in irrigation can be achieved merely by the usage of more groundwater and without improvement in more productive use of this water.

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