Volume 24, No.-4
Oct- Dec, 2009

Bhu-Jal NEWS

Quarterly Journal

CENTRAL GROUND WATER BOARD
MINISTRY OF WATER RESOURCES
GOVERNMENT OF INDIA

भू-जल न्यूज़

Quarterly Journal of Central Ground Water Board
Ministry of Water Resources
Government of India

* The status of members of the editorial Board is as on 01.02.2011
The Statement and opinions expressed by authors in this Journal are not necessarily those of the Government.

Published by **Chairman**, Central Ground Water Board, Ministry of Water Resources, Bhu-Jal Bhawan, NH-IV, Faridabad-121 001 (Haryana).

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Bhu-Jal News - Quarterly Journal of Central Ground Water Board with the objective to disseminate information and highlight various activities and latest technical advances in the field of Ground Water.

Inside

Editorial

Chairman's Page

Bhujal News*, our in-house esteemed journal is now entering into its 25th year of publication in 2010. Special volumes on important issues are being planned for publication during this year. The main objective of this journal is to disseminate the technical information as well as latest research in ground water. All efforts have been made including hosting the recent issues in the website of CGWB to ensure its wider reach.*

The importance of ground water in Indian economy & public health is well accepted & is influenced by social, environmental and economical considerations. Accurate assessment of ground water resources is of prime importance for further planning and management of this vital resources. Sustainable water management in India is fast becoming a necessity with the looming crisis over water resources in the country. It is a challenge for food security and livelihood of the population and the environment. Central Ground Water Board, the apex organisation on ground water sector in India, has come a long way in exploring the potential aquifers through various scientific techniques in the country. In addition the Board has provided assistance in disaster mitigation activities during Latur earthquake in 1993, Bhuj earthquake in 2001, Super cyclone in Orissa during 2000 and Tsunami hit coastal belt of Tamil Nadu & Kerala and Andaman & Nicobar Islands in 2004 by way of construction of tube wells for water supply.

This issue is a part of Ground Water Session of 5th Asian Regional Conference on "Improvement in Efficiency of irrigation projects through Technology upgradation and better operation & Maintenance" , organised by INCID with CGWB, held on 6-11th December 2009 at New Delhi. I am sure the readers shall be benefited from the selected papers published in Bhujal News.

Dr S.C.Dhiman
Chairman, CGWB

Picture of Editor

Editorial

The present issue contains 9 selected papers presented under Ground Water Session of 5th Asian Regional Conference on "Improvement in Efficiency of irrigation projects through Technology upgradation and better operation & Maintenance" , organised by Indian National Committee on irrigation and drainage(INCID) held on 6-11th December 2009 at New Delhi.

Jha & Sinha in their paper " Towards better management of ground water resources in India" addressed the various strategies for ground water management in the country. Tushar Shah elaborated the India's ground water irrigation economy since 19th century. S.P.Wani et.al detailed the issues of sustainable development and management of the groundwater resource through integrated watershed management (IWM) approach relative to food production and security. Shri Rajendra Singh through his paper outlines the community driven approach for artificial recharge using traditional techniques of water harvesting. Shri V.Damle emphasized through his paper about sectoral allocation and pricing of ground water. Dr Dhiman & Thambi have described the ground water management strategies in coastal areas. Shri Sushil Gupta addressed the ground water management issues in Alluvial areas of Punjab. Shri Ravider Kaur & K.G.Rosin through his paper attempts to illustrate the existing groundwater vulnerability assessment approaches and challenges for wide scale application under Indian conditions. Dr Mukherji, etal have discussed the hydrogeomorphological microzonation to infer ground water potential and quality in NCR

Sincere efforts have been made to make this issue more informative and useful. It is hoped that findings of the papers in this issue will benefit our readers.

Dr S.K.Jain
Editor

Towards Better Management of Ground Water Resources in India

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Abstract

Groundwater is the most preferred source of water in various user sectors in India on account of its near universal availability, dependability and low capital cost. The increasing dependence on ground water as a reliable source of water has resulted in indiscriminate extraction in various parts of the country without due regard to the recharging capacities of aquifers and other environmental factors. On the other hand, there are areas in the country, where ground water development is sub-optimal in spite of the availability of sufficient resources, and canal command areas suffering from problems of water logging and soil salinity due to the gradual rise in ground water levels. As per the latest assessment, the annual replenishable ground water resource of the country has been estimated as 433 billion cubic meter (bcm), out of which 399 bcm is considered to be available for development for various uses. The irrigation sector remains the major consumer of ground water, accounting for 92% of its annual withdrawal. The development of ground water in the country is highly uneven and shows considerable variations from place to place. Though the overall stage of ground water development is about 58%, the average stage of ground water development in North Western Plain States is much higher (98%) when compared to the Eastern Plain States (43%) and Central Plain States (42%). Management of ground water resources in the Indian context is an extremely complex proposition. The highly uneven distribution and its utilization make it impossible to have single management strategy for the country as a whole. Any strategy for scientific management of ground water resources should involve a combination of supply side and demand side measures depending on the regional setting.

As far as ground water resource availability is concerned the share of alluvial areas covering Eastern Plain states of Bihar, Orissa (part), Eastern Uttar Pradesh and West Bengal and North Western plain states of Delhi, Haryana, Punjab, Western Uttar Pradesh, Chandigarh; is about 44% of the total available resource. However, these groups of states have overall development of the order of 43% and 98% respectively. In view of the marked difference in stage of ground water in these areas, there is a need to critically analyze the underlying factors responsible for the imbalances in terms of technical and socio-economic considerations. These should also be taken for consideration while formulating any comprehensive water resources management initiatives for the country. There is urgent need for coordinated efforts by various Governments and non-governmental agencies, social service organizations and the stakeholders for evolving implementable plan for effective management of this precious natural resource.

Introduction

Groundwater has emerged as the predominant democratic water source and poverty reduction tool in India's rural areas. On account of its near universal availability, dependability and low capital cost, it is the most preferred source of water to meet the requirements of various user sectors in India. Ground water has made significant contributions to the growth of India's Economy and has been an important catalyst for its socio economic development. Its importance as a precious natural resource in the Indian context can be gauged from the fact that more than 85 percent of India's rural domestic water requirements, 50 percent of its urban water requirements and more than 50 percent of its irrigation requirements are being met from ground water resources. The increasing dependence on ground water as a reliable source of water has resulted in its large-scale and often indiscriminate development in various parts of the country, without due regard to the recharging capacities of aquifers and other environmental factors.

The unplanned and non-scientific development of ground water resources, mostly driven by individual initiatives has led to an increasing stress on the available resources. The adverse impacts can be observed in the form of long-term decline of ground water levels, de-saturation of aquifer zones, increased energy consumption for lifting water from progressively deeper levels and quality deterioration due to saline water intrusion in coastal areas in different parts of the country. On the other hand, there are areas in the country, where ground water development is still at low-key in spite of the availability of sufficient resources, similarly the canal command areas suffer from problems of water logging and soil salinity due to the gradual rise in ground water levels.

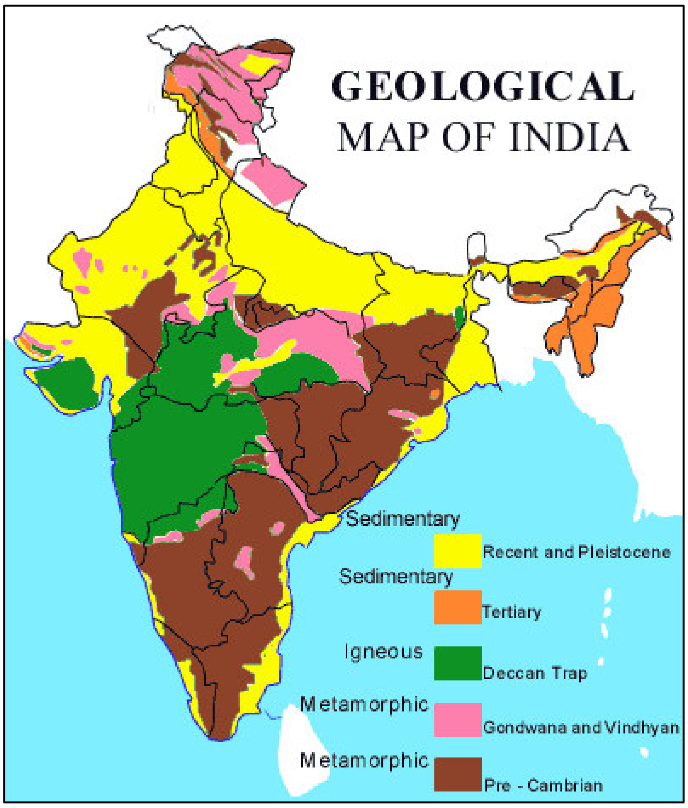
In order to address various issues related to ground water, keeping in view the climatic change, there is a need to prepare a comprehensive road map with identified strategies for scientific and sustainable management of the available ground water resources in the country so as to avert the looming water crisis. In addition to addressing the issues of declining water level, the strategies should also focus on the imbalances in ground water development in the country, reasons thereof and suggesting measures including accelerated development of ground water in areas with low stage of ground water development.

Hydrogeological Set -up of the Country

India is a vast country with a highly diversified hydrogeologic set-up. The ground water behavior in the Indian sub-continent is highly complicated due to the occurrence of diversified geological formations with considerable lithological and chronological variations, complex tectonic framework, climatological dissimilarities and various hydrochemical conditions. The rock formations range in age from Archaean to Quaternary-Recent period. The Archaean rocks are present in the southern states where as the recent sediments are confined to Indo-Gangetic alluvial plains. The major Geological Formations are the –

1) Consolidated formations represented by Igneous & Metamorphic rocks with major rock types consisting of granites, Charnockites, Quartzites & associated Phyllite, slate etc; basalts & associated igneous rocks.
2) The semi consolidated rock formations are represented by rocks of Mesozoic & tertiary period with major rock types represented by limestone, sandstone, pebbles & boulder conglomerates.
3) The unconsolidated formations belong to Pleistocene to recent period & represented by major rocks such as boulders, pebbles, different grade of sands, silt-clay. These rocks form the major potential aquifer zones.

Figure 1 : Geological Map of India (Source: GSI)



The Indian sub continent is occupied by major geological rock types such as metamorphics of pre Cambrian period, Igneous rocks represented by basaltic rocks of Cretaceous-Eocene period, Gondwana & Vindhyan rocks which are overlain by quaternary to recent sedimentary deposits .The distribution of these rock types are given in geological map (Figure 1).

Based on the formation characteristics and hydraulic properties to store and transmit ground water hydrogeologically all the litho units can be placed under two broad groups of water bearing formations Viz. ***Porous Formations*** which can be further classified into unconsolidated and semi consolidated formations having the primary porosity and ***Fissured Formation* or Consolidated** formations which has mostly the secondary or derived porosity. The Hydrogeological map showing the broad group of consolidated and unconsolidated water bearing formations along with their yield prospects are shown in F**ig.2**.

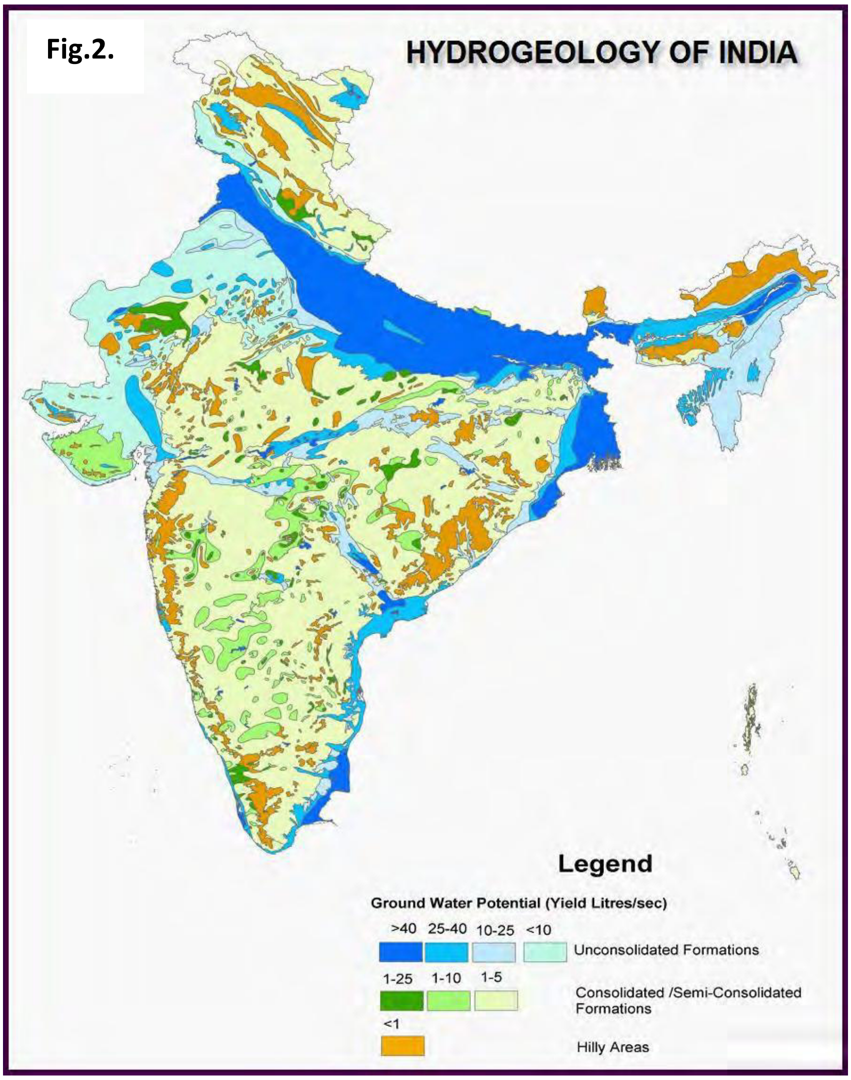


Figure 2 : Hydrogeology of India (Source: CGWB)

Physiographic and geomorphologic settings are among the important factors that control the occurrence and distribution of ground water. Based on these factors, the country has been broadly divided into five distinct regions as below:

i) **Northern Mountainous Terrain and Hilly areas**: The highly rugged mountainous terrain in the Himalayan region in the northern part of the country extending from Kashmir to Arunachal Pradesh is characterized by steep slopes and high runoff. This region is underlain mostly by rocks such as granites, slate, sandstone and lime stone ranging in age from Paleozoic to Cenozoic. The yield potential ranges from 1 to 40 lps. Though this area offers very little scope for groundwater storage, it acts as the major source of recharge for the vast Indo-Gangetic and Brahmaputra alluvial plains.

ii) **Indo-Gangetic-Brahmaputra Alluvial Plains**: This region encompasses an area of about 850,000 sq km covering states of Punjab, Haryana, Uttar Pradesh, Bihar, Assam and West Bengal, accounting for more than one fourth of country's land area, comprises the vast plains of *Ganges* and *Brahmaputra* rivers and are underlain by thick piles of sediments of Tertiary and Quaternary age. This vast and thick alluvial fill, exceeding 1000 m at places, constitute the most potential and productive ground water reservoir in the country. These are characterized by regionally extensive and highly productive multi-aquifer systems. The ground water development in this region is still sub-optimal, except in the states of Haryana and Punjab. The deeper aquifers available in these areas offer good scope for further exploitation of ground water with suitable measures. In Indo-Gangetic- Brahmaputra plain, the deeper wells have yield ranging from 25-50 lps.

iii) **Peninsular Shield Area**: These are located south of Indo-Gangetic-Brahmaputra plains and consist mostly of consolidated sedimentary rocks, *Deccan Trap* basalts and crystalline rocks in the states of Karnataka, Maharashtra, and Tamil Nadu, Andhra Pradesh, Orissa and Kerala. Occurrence and movement of ground water in these formations are restricted to weathered residuum and interconnected fractures at deeper levels and they have limited ground water potential. The rocks are commonly weathered to a depth of 30m under the tropical conditions in central and southern part of the peninsular region. Ground water occurs mainly in the weathered and fractured zones of rocks, within depth of less than 50m, occasionally down to 100m, and rarely below this depth. Locally deep circulation of ground water is indicated, as instanced by striking solution cavities or deeper water bearing fractures. Ground water development is largely through dug wells. The valley fills in this region are often dependable sources of water supply. The yield of wells tapping deeper fractured zones in hard rocks varies from 2-10 lps.

iv) **Coastal Area**: Coastal areas have a thick cover of alluvial deposits of Pleistocene to Recent age and form potential multi-aquifer systems in the states of Gujarat, Kerala, Tamil Nadu, Andhra Pradesh and Orissa. However, inherent quality problems and the risk of seawater ingress impose severe constrains in the development of these aquifers. In addition, the ground water over-development in these areas entails the risk of saline water ingress. Ground water prospects in these aquifers vary widely depending on the local conditions and may range from 5-25 lps.

v) **Cenozoic Fault Basin and Low Rainfall Areas**: This region has been grouped separately owing to its peculiarity in terms of presence of three discrete fault basins, the Narmada, the Purna and Tapti valleys, all of which contain extensive valley fill deposits. The fill ranges in thickness from about 50 to 150 m. The aquifer systems in arid and semi-arid tracts of this region in parts of Rajasthan and Gujarat receive negligible recharge from the scanty rains and the ground water occurrence in these areas is restricted to deep aquifer systems tapping fossil water. For example, in parts of Purna valley the ground water is extensively saline and unfit for various purposes. The yield potential of the wells varies from 1-10 lps.

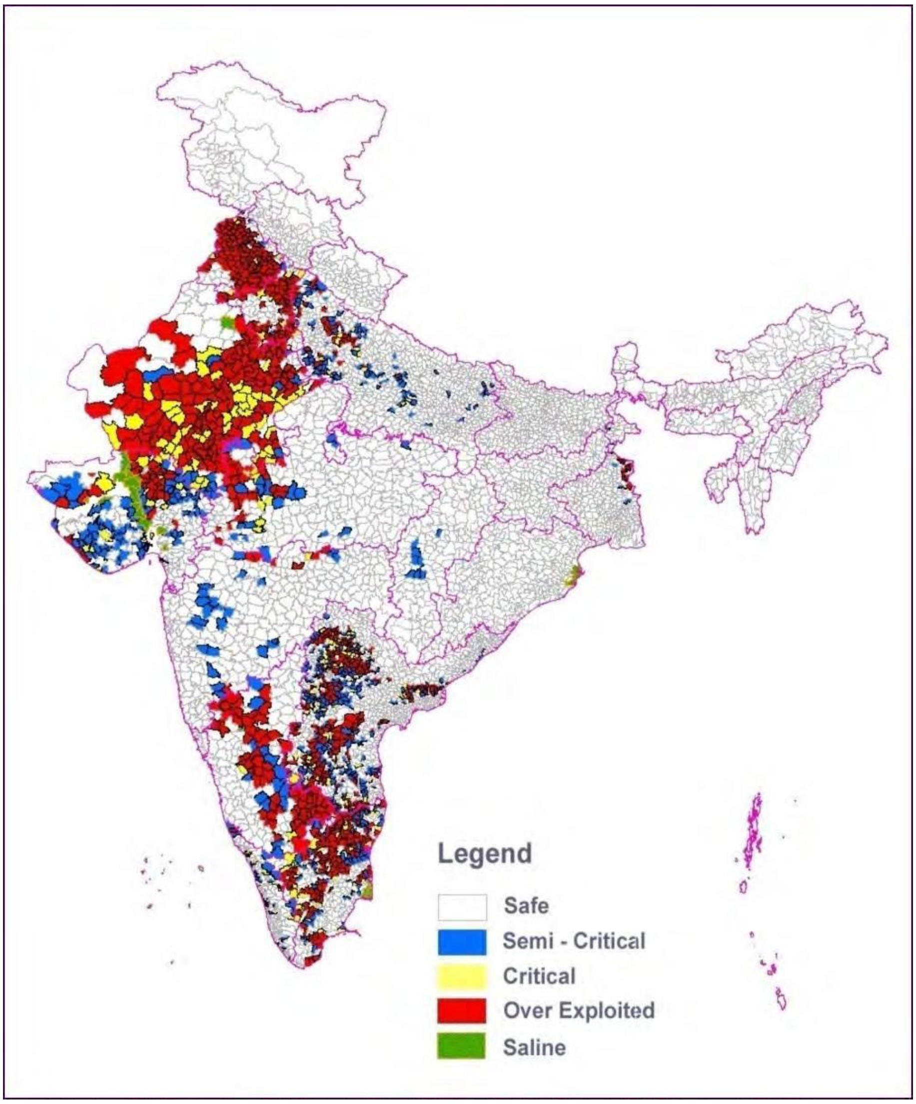
Ground Water Resources Availability

Rainfall is the major source of ground water recharge in India, which is supplemented by other sources such as recharge from canals, irrigated fields and surface water bodies. A major part of the ground water withdrawal takes place from the upper unconfined aquifers, which are also the active recharge zones and holds the replenishable ground water resource. The replenishable ground water resource in the active recharge zone in the country has been assessed by Central Ground Water Board jointly with the concerned State Government authorities. The assessment was carried out with Block/Mandal/Taluka/Watershed as the unit and as per norms recommended by the Ground Water Estimation Committee (GEC)-1997. As per the latest assessment, the annual replenishable ground water resource in this zone has been estimated as 432 billion cubic meter (bcm), out of which 399 bcm is considered to be available for development for various uses after keeping 34 bcm for natural discharge during non-monsoon period for maintaining flows in springs, rivers and streams (Central Ground Water Board, 2006).

Ground water extraction for various uses and evapotranspiration from shallow water table areas constitute the major components of ground water draft. In general, the irrigation sector remains the main consumer of ground water. The ground water draft for the country as a whole has been estimated as 231 bcm (Central Ground Water Board, 2006), about 92 percent of which is utilized for irrigation and the remaining 8 percent for domestic and industrial uses. Hence, the stage of ground water development, computed as the ratio of ground water draft to total replenishable resource, works out as about 58 percent for the country as a whole. However, the development of ground water in the country is highly uneven and shows considerable variations from place to place.

As a part of the resource estimation following the GEC norms, the assessment units have been categorized based on the stage of ground water development and long term declining trend of ground water levels. As per the assessment, out of the total of 5723 assessment units in the country, ground water development was found to exceed more than 100 % of the natural replenishment in 839 units (14.7 %) which have been categorized as 'Over-exploited'. Ground water development was found to be to the extent of 90 to 100 percent of the utilizable resources in 226 assessment units (3.9 %), which have been categorized as 'Critical'. 550 assessment units with stage of ground water development in the range of 70 to 100 % and long-term decline of water levels either during pre- or post-monsoon period have been categorized as 'Semi-Critical' and 4078 assessment units with stage of ground water development below 70% have been categorized as 'Safe'. 30 assessment units have been excluded from the assessment due to the salinity of ground water in the aquifers in the replenishable zone. Salient details of ground water resource availability, utilization, stage of development and categorization of assessment units for the above Regions of the country is given in **Table.1 and** geographic distribution of various categories of assessment units is shown in **Fig.3.**

Fig.3 Geographical Distribution of Various Categories of Assessment Units in India (Source-CGWB)



In addition to the resources available in the zone of water level fluctuation, extensive ground water resources have been proven to occur in the deeper confined aquifers in the country, a major chunk of which is in the Ganga-Brahmaputra alluvial plains (Romani, 2006). Such resources are also available in the deltaic and coastal aquifers to a lesser extent. These aquifers have their recharge zones in the upper reaches of the basins. The resources in these deep-seated aquifers are termed 'In-storage ground water resources'. The quantum of these resources has been tentatively estimated as ~10,800 bcm. Though the ground water resources in these aquifers are being exploited to a limited extent in parts of Punjab, Haryana and western Uttar Pradesh, detailed studies are to be taken up to fully understand the yield potentials and characteristics of these aquifers.

Table.1. Ground Water Resources Availability and Status of its Utilization in India

Regions	Annual Replenish-able Ground Water Resource (bcm)	Natural Discharge during non-monsoon season (bcm)	Net Annual Ground Water Available (bcm)	Annual Ground Water Draft (bcm)	Stage of Ground Water Development (%)	Categorization of Assessment Units (Blocks / Mandals)		
						Total Assessment Units	Over Exploited, Nos / %	Critical Nos / %
Northern Himalayan states	5.4	0.48	4.92	1.84	37	30	2/6.67	0
North Eastern Hilly States	33.99	3.02	30.98	5.63	18	118	0/0	0
Eastern Plain States	111.63	9.03	102.5	43.97	43	1895	1/.05	2/.11
North Western Plain States	80.78	6.92	73.85	72.17	98	277	201/72.56	28/10.11
Western arid Region	27.38	1.97	25.4	24.48	96	462	172/37.23	62/13.42
Central Plateau States	90.723	5.19	85.53	36.11	42	985	31/3.15	6/.61
Southern Peninsular States	82.78	7.14	75.65	46.4	61	1946	432/22.2	128/6.58
Islands	0.34	0.01	0.32	0.01	4	10	0	0
Country Total	433.02	33.77	399.26	230.63	58	5723	839	226

Note:
Southern peninsular states – Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Pondicherry; *North Eastern hilly states* – Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura; Eastern plain states – Bihar, Orissa (part) , Eastern Uttar Pradesh and West Bengal; *Central Plateau states* – Chhattisgarh, Jharkhand, Madhya Pradesh, Maharashtra, Dadra & Nagar Haveli; *North Western plain states* – Delhi, Haryana, Punjab, Western Uttar Pradesh, Chandigarh; *Western arid states* – Gujarat, Rajasthan, Daman & Diu; *Northern Himalayan states* – Himachal Pradesh, Jammu & Kashmir, Uttarakhand; *Islands* – Andaman & Nicobar, Lakshadweep.

Management of Ground Water Resources

Management of ground water resources in the Indian context is an extremely complex proposition as it deals with the interactions between the human society and the physical environment. The highly uneven distribution of ground water availability and its utilization indicates that no single management strategy can be adopted for the country as a whole. On the other hand, each situation demands a solution which takes into account the geomorphic set-up, climatic, hydrologic and hydrogeologic settings, ground water availability, water utilization pattern for various sectors and the socio-economic set-up of the region.

Any strategy for scientific management of ground water resources involves a combination of A) Supply side measures aimed at increasing extraction of ground water depending on its availability and B) Demand side measures aimed at controlling, protecting and conserving available resources. Various options falling under these categories are described in detail in the following sections.

Supply Side Measures:-As already mentioned, these measures are aimed at increasing the ground water availability, taking the environmental, social and economic factors into consideration. These are also known as 'structural measures', which involves scientific development and augmentation of ground water resource. Development of additional ground water resources through suitable means and augmentation of the ground water resources through artificial recharge and rainwater harvesting fall under this category. For an effective supply-side management, it is imperative to have full knowledge of the hydrologic and hydrogeologic controls that govern the yields of aquifers and behavior of ground water levels under abstraction stress. Interaction of surface and ground water and changes in flow and recharge rates are also important considerations in this regard.

(i) Scientific Development of Ground Water Resources
  a) Ground Water Development in Alluvial Plains
  b) Ground Water Development in Coastal Areas
  c) Ground Water Development in Hard Rock Area
  d) Ground Water Development in Water-logged Areas
  e) Development of Flood Plain Aquifers

(ii) Rainwater Harvesting and Artificial Recharge

Demand Side Measures:-Apart from scientific development of available resources, proper ground water resources management requires to focus attention on the judicious utilization of the resources for ensuring their long-term sustainability. Ownership of ground water, need-based allocation pricing of resources, involvement of stake holders in various aspects of planning, execution and monitoring of projects and effective implementation of regulatory measures wherever necessary are the important considerations with regard to demand side ground water management.

Groundwater Development Prospects in India

The analysis of available data indicates that contribution made by ground water to the agricultural economy of India has grown steadily since early 1970's. In just last two decades, the ground water irrigated lands in India has increased by nearly 105%, this change was most striking in northern India, the heart of the Green Revolution.

A close examination of the ground water resource availability in different geomorphological terrains of the country and its utilization as presented in Table 1, indicates that out of the total of 433 BCM of annual replenishable ground water resources available in the country , the share of alluvial areas covering Eastern Plain states of Bihar, Orissa (part) , Eastern Uttar Pradesh and West Bengal; *and* North Western plain states of Delhi, Haryana, Punjab, Western Uttar Pradesh, Chandigarh; is about 192 BCM which is works out to be 44% of the total available resource. The enigma is in the eastern plain states the overall stage of ground water development is about 43%, whereas the overall stage of ground water development in North Western Plain states covering Punjab, Delhi and Haryana is 98%. Except Western part of Uttar Pradesh, a major part of the area is overexploited.

A perusal of statistics of the increase in the number of mechanized wells and tube wells also illustrates how quickly ground water irrigation has spread. Number of wells rocketed in the last 40 years from less than one million to more than 19 million in the year 2000 itself as per the last census record. Further, the ground water irrigation has greater impact in poverty alleviation, as in relation to the amount of land they cultivate, poor farmers are better represented than richer farmers in their use of ground water. Small and marginal farmers (less than 2 Hectares land) make up only 20% of the total agricultural area. Yet these small farmers account for 38% of the net area irrigated by wells and 35% of the tube wells fitted with electrical pump sets.

Probably, the time has come to focus our attention on analyzing the imbalances on the use of ground water. There is no doubt that overuse of ground water is occurring in isolated areas, and it can have devastating effects on communities. This leads to two burning questions about ground water overexploitation, why are some areas affected and not others? How can be it be pre determined or predicted? The answer becomes clear when one key point is understood: ground water use is dependent on Demand, not Supply. The fact that ground water is tapped only where there are large aquifers, or a lot of rainfall or surface irrigation systems exists – which results in more recharge to ground water may not be true in strict sense. This can be very well visualized from the fact that in spite of abundance of ground water resources, the utilization in the Eastern Plain states of Bihar, West Bengal is much less as compared to Punjab and Haryana. This proves the fact that ground water use is purely Demand driven. There might have been several reasons for less demand of water in the eastern states, but the fact remains that, there is ample scope of ground water development in these areas so as to balance the ground water use of country.

Hence, there is an urgent need to have a comprehensive accelerated ground water development plan for the areas having low stage of development and further scope for ground water development which should go parallel with the measures for ground water augmentation. The ground water governance must include the supply side management

Coastal Areas:- Many parts of the coastal areas of India have thick deposits of sediments ranging in age from Pleistocene to recent, which have given rise to multi-aquifer systems of good potential. There is considerable scope for development of ground water from such aquifer systems. However, development of ground water from such aquifers needs to be done with caution and care should be taken to ensure that over-exploitation of resources does not lead to saline water intrusion.

Large diameter dug wells, filter point wells and shallow tube wells are ground water abstraction structures best suited for such aquifers. Radial wells and infiltration galleries can also be constructed in areas where the requirement of water is large. As the multi-aquifer systems in coastal areas are likely to have all possible dispositions of fresh and saline waters, it is necessary to take-up detailed studies to establish the saline–fresh water interface and establish the replenishable discharge of ground water to sea. This will ensure the implementation of ground water development plans. Further, sanctuary wells need to be constructed in hydrogeologically suitable areas to meet the unforeseen situations during cyclonic disasters as well as Tsunamis.

Water-logged Areas:-Water-logging and soil salinity problems, resulting from gradual rise of ground water levels, are observed in many canal command areas due to the implementation of surface water irrigation schemes without due regard to environmental considerations. As per the assessment made by the Working Group on Problem Identification with Suggested Remedial Measures (1991), about 2.46 million hectare of land under surface water irrigation projects in the country is either water-logged or under threat of it. Such areas offer good scope for further ground water development as the shallow water table in such areas can be lowered down to six meters or more without any undesirable environmental consequences. The problems related to inferior quality of water in such areas can be solved by mixing them with the canal waters available. Judicious development through integrated use of surface and ground water resources can greatly reduce the menace of water-logging and salinity in canal irrigated areas. Such efforts will also be in line with the directives of National Water Policy which states that surface and ground water should be viewed as an integrated resource and should be developed conjunctively in coordinated manner and their use should be envisaged right from the project planning stage.

Development from Deep Aquifers:-The stage of ground water development is rather high in the States of Haryana, Punjab and Rajasthan and a large number of over-exploited and critical assessment units fall in these states. Studies by CGWB in the Indo-Gangetic basin in Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal have revealed the existence of deep-seated aquifers storing voluminous quantity of ground water. Fresh ground water has been reported down to a depth of about 700 m in Uttar Pradesh. Exploratory studies carried out by ONGC in the Gangetic alluvium indicated existence of fresh ground water at more than 1000 m depth. Similarly, free flow of ground water due to artesian conditions exists in some areas like Tarai and sub-Tarai belt of Uttar Pradesh and Bihar. As no energy is required for extraction of ground water from such aquifers, development of ground water from these auto-flow zones is both economically viable and eco-friendly.

Flood Plain Aquifers:-Flood plains of rivers are normally good repositories of ground water and offers excellent scope for development of ground water. Ground water levels in these tracts are mostly shallow, leaving little room for accommodating the monsoon recharge, a major portion of which flows down to the river as surface (flood) and sub-surface runoff. A planned management of water resource in these tracts can capture the surplus monsoon runoff, which otherwise goes waste. The strategy involves controlled withdrawal of ground water from the flood plains during non-monsoon season to create additional space in the unsaturated zone for subsequent recharge/infiltration during rainy season.

There are two distinct conditions as regards to induced recharge from the river/stream to ground water aquifer. The first condition involves setting up a hydraulic connection between the aquifer and the river as recharge boundary due to heavy exploitation of ground water and expansion of cone of depression. This condition is common in case of perennial rivers and leads to changes in river flow conditions in the downstream.

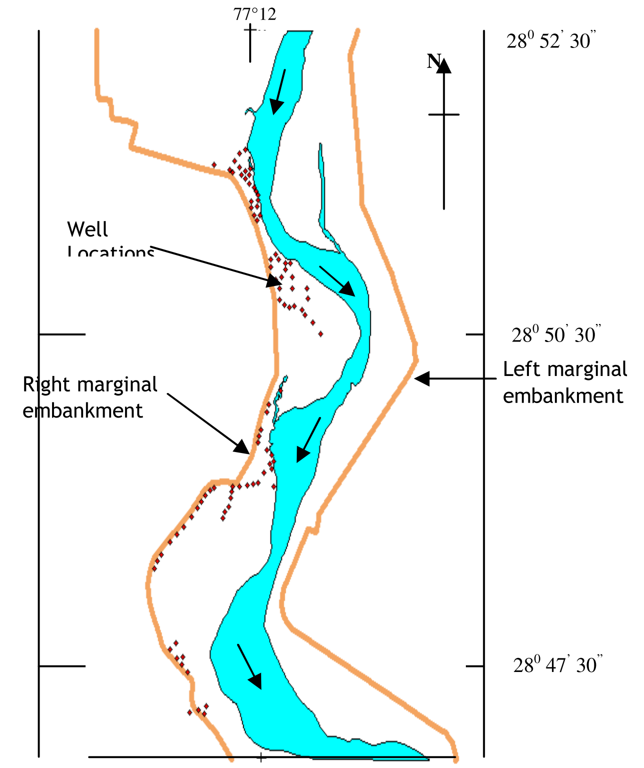


Fig. 4 Ground Water Development in Yamuna flood plain, Palla sector, Delhi

The hydraulic connection between the river and the aquifer ceases as soon as pumping is stopped. The second scenario is more common in case of rivers having intermittent flows; the loose sediments in the flood plains are more or less saturated resulting into shallower ground water level. The heavy withdrawal of such flood plain aquifers during the non-monsoon creates ample space in the ground water reservoir which gets recharged by the river during the flood season. In absence of such created space the river water would overflow. This condition is more prevalent in Indian scenario and provides opportunity for augmentation of ground water reservoir through induced recharge.

A study in this regard was taken up in northern part of Yamuna flood plain area in Delhi (Fig.4) wherein Central Ground Water Board constructed 95 tube wells in Palla Sector in the depth range of 38-50 m for Delhi Jal Board, the domestic water supply agency of the State. On the basis of scientific studies, it was found out that nearly 30 MGD of water can be safely drawn from these tube wells during monsoon and non-monsoon seasons to meet drinking water requirements of National Capital Territory, Delhi (NIH & CGWB, 2006). In this process, a part of flood water (rejected recharge) is utilized to augment sub-surface storage during monsoon.

The experience of Yamuna flood plains in Delhi has shown the scope of enhancing ground water recharge by pumping to lower the water table ahead of the rainy season and thus creating more space for the flood water to percolate. The concept can be implemented in similar situations in different parts of the country after carrying out detailed study on the ground water development prospects of the flood plains involving stream-aquifer interaction.

Alluvial Areas (Indo Gangetic Plains):-Scientific studies have proven that ample reserve of ground water is available in the areas underlain by Indo - Gangetic and Brahmaputra alluvial plains in the northern and northeastern parts of the country. Coincidently, the ground water developments in these areas are sub-optimal, in spite of the availability of resources, and offers considerable scope for ground water development in future. In addition to the sufficient availability of replenishable ground water resources in the phreatic zone, there is a vast In-storage ground water resource in the deeper zones i.e. below the zone of ground water fluctuation. The estimates of In storage ground water resources on the prorate basis up-to a depth of 400 m works out to be 10812 bcm , out of which nearly 10633 bcm is available in the areas occupied by alluvial and unconsolidated formations. Surprisingly the three major States occupying the alluvial plains i.e. Uttar Pradesh, Bihar and West Bengal, has a share of the in storage ground water resources to the tune of 7652 bcm which is more than 70% of the total.

Fragmented land holdings, poor socio-economic status, poor infrastructure facilities, lack of knowledge of modern technologies are some of the reasons for the under-utilization of ground water resources in these areas , in spite of the growing need for boosting agricultural production. In this context there is an urgent need to explore various befitting options for optimal utilization of these resources.

Rainwater Harvesting and Artificial Recharge:-Rainwater harvesting and artificial recharge have now been accepted worldwide as cost-effective methods for augmenting ground water resources and for arresting/reversing the declining trends of ground water levels. Artificial recharge techniques are highly site-specific. Need, suitability of area in terms of availability of sub-surface storage space and availability of surplus monsoon run-off is important considerations for successful implementation of artificial recharge schemes.

Rainwater harvesting and artificial recharge schemes implemented by various organizations in the country including Central Ground Water Board have shown encouraging results in terms of augmentation of ground water recharge, check in rate of decline of ground water levels and reduction of surplus run off. Increased sustainability of existing abstraction structures, increase in irrigation potential, revival of springs, soil conservation through increase in soil moisture and improvement in ground water quality are among other benefits of the schemes. In the coastal tracts, tidal regulators, constructed to impound the fresh water upstream and enhance the natural recharge are effective in controlling salinity ingress.

Experience gained from pilot artificial recharge schemes implemented by Central Ground Water Board in different hydrogeological settings in the country has indicated that optimal benefits can be achieved when various recharge structures are constructed at suitable locations in complete hydrological units such as watersheds, sub-basins etc.

Central Ground Water Board has also carried out studies for demarcating areas of long-term decline of ground water levels and for exploring the possibility of augmenting the ground water resources in these aquifers using available surplus monsoon runoff. An area of about 4.5 lakh sq km has been identified in the country where such augmentation measures are considered necessary. It has also been estimated that about 36 BCM of surplus monsoon runoff can be recharged into these aquifers annually (CGWB, 2002). Modification of natural movement of surface water into the aquifers through various structures like check dams, percolation ponds, recharge pits, shafts or wells are considered suitable in rural areas. On the other hand, roof-top rainwater harvesting, either for storage and direct use or for recharge into the aquifers is suited for urban habitations with its characteristic space constraints. There is a need to shift the initiative from institutional endeavor and make it into a mass movement. Community based programmes on rain water harvesting and artificial recharge would inculcate a sense of responsibility among the stake holders, thereby enhancing the efficiency level of maintenance of the schemes.

Demand Side Measures

Apart from scientific development of available resources, proper ground water resources management requires to focus attention on the judicious utilization of the resources for ensuring their long-term sustainability. Ownership of ground water, need-based allocation and pricing of resources, involvement of stake holders in various aspects of planning, execution and monitoring of projects and effective implementation of regulatory measures wherever necessary are the important considerations with regard to demand side ground water management.

Regulation of Ground Water Development: Regulation of over-exploitation of ground water through legal means can be effective under extreme situations if implemented with caution. Ground water regulatory measures in India are implemented both at Central and State level. The central Ground Water Authority, constituted under Environment (Protection) Act of 1986 is playing a key role in regulation and control of ground water development in the country. Central Ground Water Authority initially notifies over-exploited areas in a phased manner for registration of ground water abstraction structures. Based on data thus generated, vulnerable areas are notified for the purpose of ground water regulation. In these areas, construction of new ground water abstraction structures is regulated.

As water is a State subject, the management of ground water resources is a prerogative of the concerned State Government. Ministry of Water resources has prepared and circulated Model Bills to all States and Union Territories during 2005. The main thrust of these bills is to ensure that all the States and Union Territories form their own State Ground Water Authorities for proper control and regulation of ground water resources. As water is a basic need and thereby an important social issue, the regulatory mechanism needs to be transparent and people-friendly. Continuous monitoring of ground water regime is required in notified areas.

Micro-level studies needs to be taken up in such areas on a regular basis to assess the impacts of the regulatory measures on the ground water regime. Real-time dissemination of information on the ground water situation in the affected areas is to be provided to the stakeholders. Involving local people in the administrative process as social volunteers may also help.

International experiences in ground water regulation and management are varied. United States ground water management practices are more in the form of financial incentives. In Spain and Mexico, water laws are formulated making ground water a national property. However, implementation of various clauses of ground water legislation could not be effectively achieved on a large scale in these countries (Planning Commission, 2007). National and international experiences indicate that enforcement of legislative measures for ground water regulation and management would be meaningful only when stakeholders are motivated through local self governing bodies and directly involved in the decision-making and enforcement process.
In the present paper an attempt has been made to present the ground water development scenario and ground water development prospects in the Indo Gangetic plain taking the case studies of the State of Bihar, Punjab and West Bengal.

Prospects of Groundwater Development in Indo-Gangetic Plains

Bihar :-Bihar is undergoing fast economic development with its impact on life style, natural resources and environment. But economic growth has persisting inadequacies. One such challenging area is agriculture, which has the key role in poverty alleviation in Bihar, where 90% population is rural. Though the state is bestowed with water and land, the state needs to substantially increase the cropping intensity and also the irrigation intensity. Assured availability of water for drinking, agriculture and industries are the key factors to determine the future economic scenario.

During the last six decades, the remarkable feature in irrigation development is the conspicuous growth in the use of groundwater. However, in Bihar at present, the groundwater meets the irrigation to only about 65 % of the gross irrigated area. It has affected the agricultural production for want of irrigations. The major credit for increase in groundwater use goes to a large extent to the farmers' own investment and spread of groundwater market.

There are about 0.9 million shallow and about 1700 deep tube wells in operation in the state. Besides, ground water caters the entire domestic water supply for ~ 8.3 Crore population. Even then, the stage of groundwater development is only 39%. To enhance the irrigation potential ground water can safely be developed at least to the level of 60-70% as groundwater irrigation is under the direct control of the farmers and is amenable to precision agriculture and higher irrigation efficiency (Sharma, 2009). It is essential particularly in the North Bihar Plain which gives tremendous scope owing to conducive hydrogeological condition and shallow water level. While in the South Bihar Plain, along with the development of groundwater it is necessary that the artificial recharge schemes are implemented. In this regard the status of groundwater development is discussed below.

Ground Water Development Status

Bihar, with 94,163 sq.km area is one of the densely populated states of India with an average population density of 880 persons/sq km, compared to countrywide average of 325 persons/sq km (2001 census). Only 10% of the total population is urban. About 90% geographical area of the state is underlain by Gangetic alluvium brought down by the river Ganga and its Himalayan and peninsular tributaries. The remaining area exhibits piedmont surface and undulating hills of Chhota Nagpur granite gneiss of Precambrian age and Vindhyan Super group.

The Rajmahal Trap of Cenozoic age covers a narrow track in the extreme south-eastern part of the state. The alluvial plain is divided into two broad units, the north Ganga Plain covering the area north of the course of Ganga, where 17 districts are located. The alluvial plain between river Ganga and undulating hard rock terrain in south is denoted as South Ganga Plain where 21 districts are located either in full or in parts. The Ganga plain exhibits a flat monotonous terrain dotted with fluvial geomorphic landform.

The normal annual rainfall of the state is 1176 mm with an average number of 45 rainy days. About 85% of the total rainfall occurs during monsoon months. There is a pattern of increase of annual rainfall towards north . The low region along the course of River Ganga receives a rainfall of 1100 mm which gradually increases to 1500 mm in Champaran and 2100 mm in Purnea. The heavy rainfall, particularly in north Ganga Plain and in the higher catchments of Kosi and Gandak rivers in particular, causes floods. A region of rainfall (< 1000 mm) occurs in the south-central part of the state covering major areas of Nalanda and parts of Patna, Jehanabad, Nawada and Sheikhpura districts.

The aquifer system can broadly be divided into two categories (i) Fissured aquifer and (ii) Porous aquifer.

The fissured aquifers cover about 1/10th of the geographical area of the state in Rohtas, Gaya, Nalanda, Nawada, Munger, Jamui, Banka and Bhagalpur districts. Groundwater in this part occurs within the weathered zone (generally 10 to 25 m thick) and underlying secondary porosities like fractures, fissures and joints within 200 m bgl. The dug wells (8 to 12 m depth) tap low potential weathered zone. Exploratory drilling by CGWB has revealed occurrence of 2 - 5 sets of fractures underlying the weathered zone within 200 m depth. The cumulative discharge of the fractures generally remains within 5 lps. The thickness of individual fracture zone generally does not exceed 2 m. The groundwater occurs under unconfined condition within the fractured zone but long-duration pumping tests in exploratory wells of CGWB has revealed that in deeper fractured aquifer groundwater occurs under semi-confined condition at many places.

The vast Gangetic alluvial deposits covering the North and South Bihar Plains hold porous aquifer system. The drilling of CGWB dovetailing the geological information available from Geological Survey of India indicates that Quaternary deposits extends at least down to 300 m bgl in the northern part of South Ganga Plain and in major part of North Ganga Plain. In the southern part of South Ganga Plain Quaternary deposits are lying unconformably over northerly sloping Precambrian basement which is exposed as Precambrian Highlands along the southern border of Bihar state. In South Bihar Plain aquifer comprises medium to very coarse grained and sometimes gravelly sands and thus rendering a high potentiality to the aquifers. Discharge in the northern part of the unit, bordering river Ganga varies from 150 to 250m3/hr which reduces to even less than 50m3/hr in the southern part in marginal alluvial plains. Transmissivity of this aquifer varies from 6000 to 12000 m2/day and generally reduces towards south because of dual effects of reducing hydraulic conductivity and diminishing aquifer thickness. In the marginal alluvial tracts the transmissivity is generally less than 500 m2/day.

Groundwater in the productive aquifer system which is generally tapped by deep tube well, bore well and hand pumps lies under semi-confined to confined condition.

The north Bihar plain comprises two mega-fan Kosi and Gandak and vast stretches of fluvio-lacustrine deposits in between. Aquifers are comprised of medium to fine grained sand which becomes boulder towards north. At shallow level, within 50 m bgl, 1-3 zones are usually found having thickness of 3-10 m. The discharge generally ranges from 20-30 m3/day. Transmissivity of the shallow aquifer ranges from 400 to 700 m2/day and at deeper level 3-5 granular zones are encountered within 200 m bgl. The cumulative thickness ranges from 30-70 m. At places like Begusarai district the cumulative thickness of the granular zone increases considerably. In most of the wells tapping deeper aquifers, the discharge remains between 100 and 150 m3/hr. Maximum discharge is recorded as 208 m3/hr. Transmissivity ranges from 240 to beyond 6000 m2/day.

The Premonsoon water levels indicate that in major part of South Bihar Plain water level remains below 5 m bgl. Along the marginal alluvial plain bordering the Precambrian Highlands and piedmont surfaces water level goes deeper and remains below 7 m bgl. In the major part of the North Bihar Plain the level remains between 2 and 5 m bgl. During November the level remains between 2 and 5 m below ground, covering the major part of the state. In patches of South Bihar Plain the level remained between 5 to 10 m bgl.

The long term analyses of water levels do not reveal any lowering trend for any patches with significant aerial extent. However there is lack of time vs. water level data for deep aquifers. It has been reported that in major urban areas like Patna, Muzaffarpur, Ara, Gaya, Bhagalpur stress is being created on the deep aquifer system because of over withdrawal and witnessing lowering of water levels.

The state of Bihar is bestowed with substantial groundwater resources both static and replenishable. The replenishable resource represents ground water availability in the shallow aquifer between pre- and post-monsoon water level. In the state monsoon is the main source of ground water recharge. The latest assessment made as on March 31, 2004, on the basis of GEC 1997 considering community development blocks as assessment units (515 blocks). Total annual groundwater recharge has been worked out as 29.19 bcm. Considering the natural discharge during non-monsoon period Net Ground Water availability is 27.42 bcm. Existing groundwater draft for irrigation and domestic uses are 0.94 and 0.14 bcm respectively (total draft 1.08 BCM). The stage of groundwater development of the state as a whole is 39%, indicating thereby a vast scope exists for further ground water extraction. All of the 515 blocks assessed are falling under “safe” category where stage of groundwater development remains within 70%.

Below the zone of water level fluctuation (the resources which is reflected in the replenishable resource) a vast reserve of resource is available as static resources. A first approximation has been made for the in storage ground water reserve for each district separately for alluvial and the hard rock areas, for alluvial areas the resource has been worked out up to a depth of 450 m or the depth of the basement whichever is less, whereas, in hard rock areas the resource has been estimated for 100 m depth). In alluvial areas the in storage ground water reserve has been estimated as 2526 bcm, whereas in the hard rock areas it works out as 2.5 bcm

Ground water quality in the phreatic aquifer is generally good and can be safely used for drinking and irrigation uses. However , high concentration beyond the permissible limits of various chemical constituents has also been reported in different parts of the state, like high loads of arsenic, fluoride and iron from geogenic sources. Similarly , anthropogenic source like high nitrate has been reported in isolated pockets linked to high use of fertilizers.

High concentration of Arsenic (>0.50 mg/l) and Fluoride (>1.5 mg/l) in ground water is posing challenge to drinking water supply in the affected areas. Arsenic contamination is confined in the shallow aquifer system (<60 m bgl) in Holocene deposits along the course of the river Ganga. High spatial variability creates patchiness in distribution of arsenic contaminated wells. As per the latest information arsenic hotspots are distributed in 57 blocks covering 15 districts bordering River Ganga. Fluoride contamination is affecting the districts bordering the Precambrian Highlands in south. Fluoride contamination is distributed in 14 blocks of eight districts in South Bihar Plain and one block (Basantpur) in Supaul district of north Ganga Plain.

To provide assured supply for farm sector a scheme has been implemented named Million Shallow Tube Well Scheme. The intention of the scheme was to use part of the huge replenishable groundwater resource for agriculture. The 30% of the tube well and pump set cost (Rs.30 to 50 thousand) was subsidy from Govt. of Bihar, 20% was farmers' contribution and 50% as loan from the nationalized banks. The tube wells are 30 -70 m depth for the alluvial areas with a potential of 2 ha. Till date 0.4 million such shallow tube wells have been installed in the state. This scheme was sanctioned for 2001 to 2008 during 9th and 10th five year plan periods. The scheme has been replaced by a new scheme during 11th plan (2009-1012). The scheme has been named Bihar Ground Water Irrigation Scheme to harness the ground water resources.

Future Development Plan

The most important challenge for future irrigation in Bihar is its exploding population. By 2050, the population of the state is expected to cross 20 Crore. The decadal growth rate of rural and urban populations are 28.33% and 29.31% respectively. Considering per capita per day requirement of 40 liters for rural areas, the projected demand for the rural areas would be 3.782 BCM for the year 2051 against 1.083 BCM for the year 2001. There would thus be an increase of 249% in demand from the year 2001 level. For the urban areas the per capita per day requirement has been taken as 140 liters. The demand for urban areas would increase from 0.443 BCM (2001) to 1.560 BCM for the year 2051, an increase of 252% from the 2001 level.

The pressure of increasing magnitude of irrigated area in Bihar has to be mainly on groundwater. Due to reliability in water supply the yields in groundwater irrigated areas are higher. Therefore groundwater has to contribute maximum to increase substantially the irrigation intensity from 52% at present to 80%.

As on 31st March 2004, groundwater draft for irrigation was 9.39 BCM. A perusal of previous minor irrigation census data and interaction with state govt. officials indicate 1% annual increase in draft for irrigation. For the year 2009 the estimated draft for irrigation is 9.87 BCM. Keeping aside the allocation for drinking up to 2050, groundwater availability for uses other than drinking is 17.55 BCM. Considering the decadal growth of population in rural and urban areas as that of 1991-2001, total ground water draft for drinking use is 1.86 BCM for the year 2009 which would increase to 5.34 BCM in 2051. However, there is a strong possibility of increase of per capita consumption in view of betterment of life style. Keeping drinking as first priority and setting aside 5.342 BCM required for drinking in 2051, 12.21 BCM (17.55-5.34) can be diverted for enhancing the irrigation potential. This volume can provide assured irrigation to 22.42 lakh ha to enhance the irrigation intensity in Rabi and Khariff season in particular.

In storage ground water reserve in the deeper aquifers of the state is 2526 BCM out of which 99.1 BCM pertains in the alluvial deposits. A part of the static resource, particularly in North Ganga plain can be allowed to develop by large diameter deep tube wells (200m depth). The hydrogeology of the area clearly indicates that in such a case there would be adequate transfer of water from shallow to the deep aquifer system where major part of the static resource is locked. The shallow water level in mid monsoon season in large part of North Ganga plain indicates that there is lot of rejected recharge during monsoon season and evapotranspiration loss. It is believed that if ground water development is given emphasis in North Ganga plain, there would be a concomitant increase in the replenishable ground water resource. Thus the emphasis in North Ganga plain is on enhanced ground water development.

The ephemeral rivers like Phalgu, Panchanan, Morhar, Kuil etc should be harvested for making water available till the early pre-monsoon season. The recharge through the thick river bed sand deposit would help to build up the ground water resource. Water intensive industries like, sugar, agro-processing, packaged drinking water and mineral water can take the immense benefits of the copious availability of the good quality water available close to the land surface.

Enhancement of ground water extraction should not affect the water bodies that dot the north Bihar plain. Some of the water bodies are seasonal like Mokama tal in South Ganga plain. A scrupulous environmental auditing is warranted for the seasonal and perennial water bodies like cutoffs, ox-bow lakes and back swamps before any large scale increase of abstraction is contemplated for North Bihar plain.

The action plan for groundwater development in Bihar should also include

- Rehabilitation, maintenance and construction of public tube wells
- Renovation of dug wells in areas with geogenic contamination
- Artificial recharge schemes in marginal alluvium and piedmont areas of south Bihar Plains
- Groundwater abstractions using alternative (non-conventional) energy
- Estimation of evapotranspiration loss and component of rejected recharge in north Bihar plain
- Stage of groundwater development in Bihar is to be brought to 60% mainly in the North Bihar Plains,
- Groundwater ecology of water bodies in north Bihar plains
- Reclaiming water-logged areas by increasing groundwater abstractions in North Bihar Plain

Punjab:-The State of Punjab covers an area of 50362 sq.km. The population of the State is 2,43,58,999 (2001 Census) which is constituting 2.37 % of the total population of the country. The economy of the state is primarily agro based. There are six distinct physiographic zones and the State is drained by three major rivers namely Ravi, Beas and Sutlej. The State receives about 660mm normal rainfall out of which 80% occurs during southwest monsoon. July and August are the wettest months contributing about 57% of the annual rainfall. Three rivers feed a vast net work of canal system in the State and even provide water to Haryana, Rajasthan and J&K.

Punjab mainly occupies the Indo-Gangetic divide formed due to the tectonic uplift during the Pleistocene. In major part of the State, depth to water level ranges between 10 to 20mbgl. Water levels within 2.0 m occur in southwestern part in state in parts of Muktsar, Faridkot and Ferozpur districts. Shallow water levels, within 5m depth occur along flood plains of river Ravi, Satluj and Beas and in the south western part of the state. Depth to water level is more than 20 mbgl around major cities of the State viz. Amritsar, Jalandhar, Ludhiana, Moga and Sangrur. Water levels, deeper than 20m occur in Kandi areas in Hoshiarpur and Ropar districts. In the Plateau region of Garshankar block of Hoshiarpur district, it ranges between 50-180 mbgl. During the past 28 years (1975 - 2003) there is a decline in the fresh ground water areas of the State. Out of 50,362 Sq.km area of the State, 39,000 Sq.Km area (78%) exhibits a decline in water levels, covering major part of the State which includes most of Amritsar, Gurdaspur, Jalandhar, Ludhiana, Moga, Faridkot, Sangrur, Fatehgarh Sahib, Patiala, Faridkot, major part of Mansa and northern part of Ferozepur and Bathinda districts. The fall in water levels is between 4 to 16 meters. In southwestern part of the State, covering major parts of Muktsar, southern part of Ferozepur and southwestern part of Bathinda and Mansa districts and northeastern part of the State along Siwalik hills, a rise in water level has been observed.

During the past two decades, significant water table decline has been observed in most parts of Punjab. The main cause of ground water depletion is its over-exploitation to meet the increasing demand of various sectors including Agriculture, Industry and Domestic. Extensive paddy cultivation, especially during summer months has affected the available ground water resources adversely. Due to declining water table, the tube wells have to be deepened and the farmers are shifting to the use of submersible pumps in place of centrifugal pumps being used by them till now, resulting in additional expenditure and extra power consumption. This has adversely affected the socio-economic condition of the small farmers. This declining water table trend, if not checked, would assume an alarming situation in the near future affecting agricultural production and thus economy of the State and the Country. The most suitable artificial recharge methods adopted are by modifying the drain beds , abandoned river channels, village ponds,tanks and sarovar water. In a Kandi tract of the State low height dams across choes are constructed for water harvesting.

The drillings carried out in 'Kandi' and 'Beet' area has revealed that these areas possess very promising water bearing zones at deeper levels. Water levels are deep seated, These areas are being developed as high technology is available to tap the ground water resources , occurring at deeper levels. The studies have shown that these areas are ground water worthy, the green revolution has started and extending to these dry areas.

Irrigation by groundwater in the State is mainly through tube wells both shallow and deep. The shallow tube wells in the depth range of, up to 50m are owned by farmers, whereas, deep tube wells are constructed by the State Government for direct irrigation and drinking purposes. In the following 12 districts, groundwater irrigation accounts for more than 50% of the total irrigation-Hoshiarpur 82%, Gurdaspur 78.55%, Amritsar 64.55%, Kapurthala 89.4%, Jalandhar 83.5%, Patiala 94%, Fatehgarh Sahib 93.55%, Sangrur 67.31%, Ludhiana 95.6%, Ferozepur55.7%, Nawanshahar 93% and Ropar 54%.

Management Measures

Owing to steep slopes of the hills in Kandi belt falling in Hoshiarpur and Ropar districts flash floods are common in these areas and with the result there is a soil erosion in the area. With the construction of low height dams, damage of soil erosion and crops can be controlled. The depth to water in the area is deep due to which the conventional irrigation facilities like tube wells are either beyond reach of the common farmers or not feasible, and thus rendered this area backward. Micro level studies need to be taken up in the blocks which fall under over exploited category. The draft figures should be verified in the field by installing hour meters. Wherever draft has been taken on higher side, corrections may be made and recasting of water balance be carried out .Studies on Conjunctive Use of ground water and surface water resources be taken up in south western part of the State where ground water is highly mineralized and water logging has become menace.

The farmers have adopted paddy cultivation due to profitability and incentives from the Government leading to extensive development of ground water in the northern parts of the State. There is an urgent need to change the cropping pattern in these areas and to adopt cultivation of those crops which require less irrigation.

In southwestern parts of the State covering parts of Ferozepur, Faridkot, Muktsar, Bathinda and Mansa districts, the water table is rising due to limited/non-extraction of ground water because of its brackish / saline quality and thus being unfit for drinking, domestic, irrigation and other purposes .

Flood plains of Ravi, Beas and Satluj rivers are underlain by potential sub-surface reservoirs down to explored 400m depth. It is considered feasible to dewater and refill shallow aquifers on sustainable basis. This resource, which has remained unexploited could provide enormous amount of fresh ground water on sustainable basis. High capacity tube wells of about 2 cusecs (200 m^3/hr) capacity can be installed in these areas, as the underlying sandy formations are highly potential.lt would also help to reduce evaporation losses and water flowing to Pakistan during Monsoon period.

In city areas, stress on pumping of ground water is increasing to meet the ever-increasing demand of water for domestic and industrial uses. This has resulted decline of water levels at faster rates as compared to adjoining rural areas. It has been observed that in the most major cities of the State, the water levels are falling at a rate of 0.50m to 0.60m per year. This over exploitation of ground water has caused formation of ground water troughs in the central part of the cities resulting in increased energy consumption. In order to arrest the water table decline, either canal water should be supplied to the thickly populated areas or well fields may be developed in the outskirts of the cities and water be supplied through pipeline.

In the flat topped hilly areas and low hills of Siwalik, sandstones constitute good water bearing zones. These areas comprises of 'Beet area' of Garhshankar block, low hills of Dasua, Bhuga and Talwara blocks of Hoshiarpur districts. These areas require special attention to mitigate the water needs of the people. The areas have been explored by the Central Ground Water Board and proved ground water worthy.

West Bengal:-The State of West Bengal is principally an agrarian state with more than 70% of its population depend directly or indirectly on agriculture for their livelihoods. Irrigation projects account for 47.70% of the gross cropped areas of 9778815 ha (with cropping intensity 177%). Irrigation in the state is being effected through major, medium and minor irrigation programmes. About 75% of the irrigation is being done through minor irrigation schemes.

The development of agrarian economy needs expansion of irrigation facilities. The state is having huge groundwater reserve and at present the stage of groundwater development is only 42 percent of the available resources. Though huge reserve of groundwater resource is available, every drop of ground water needs proper management. Keeping the above facts in view an attempt has been made to depict the hydrogeological framework by synthesizing all the available data related to hydrogeological condition with a view to assess the ground water development prospect of the state. The Himalayan ranges from the northern boundary of the state while Bay of Bengal forms the southern boundary. Normal annual rainfall in the State ranges from 1234 mm to 4136 mm. Himalayan region receives the maximum rainfall.

The State is divided into three distinct physiographic units as

(i) Extra – Peninsular Region of the north, comprising mainly Himalayan Foot Hills, falling in Darjeeling, Jalpaiguri and Kochbehar districts

(ii) Peninsular mass of the south – west forming a Fringe of Western Plateau, covering the entire district of Purulia, western part of the districts of Barddhaman, Paschim Medinipur and Birbhum and the northern part of Bankura district

(iii) Alluvial and Deltaic plains of the south and east.
   a) Deltaic zone falling in Sundarban area of the district of South 24 Parganas and in a small part of North 24 Parganas district and
   b) Plain flat terrain falling in the remaining areas of the state.

There are three major river basins in the state namely- the Ganga, the Brahmaputra and the Subarnarekha. In the northern part of the state Teesta is the main river which along with Torsa, Jaldhaka, etc. are the tributaries of the Brahmaputra river. Mahananda is the main river meeting the Ganga in the north of the state. The state of West Bengal is covered by diverse rock types ranging from the Archaean metamorphites to the Quaternary unconsolidated sediments. Approximately two - third area of the State is covered by alluvial and deltaic deposits of Sub – Recent to Recent time and the remaining part abounds in a wide variety of hard rocks.

Nearly two-third of the state is occupied by a thick pile of unconsolidated sediments laid down by the Ganga-Brahmaputra river system, the thickness of which increases from marginal platform area in the west towards the east and southeast in the central and southern part of the basin following the configuration of Bengal Basin. These unconsolidated sediments are made up of succession of clay, silt, sand and gravel of Quaternary age overlying Mio-Pliocene sediments. The Quaternary sediments are made up of recent and older alluvium. Occurrence and movement of ground water in this hydrogeological unit is controlled by the primary porosities of the sediments.

A thick profile of in situ soft porous material develops as a disintegration product on the upper most part of the hard, consolidated rock due to weathering. Weathering imparts secondary porosity to the hard rock which either has been compact or fractured at different places under different set of conditions. Weathered mantle derived from upper part of parental hard rock, varying in thickness from <1 m to 5 m in extra-peninsular region and from 5 to 15 m in peninsular region forms the repository of ground water as shallow aquifers in the area occupied by the hard rocks. Ground water in these depositories occur under unconfined condition, and in general developed by medium to large diameter open wells, the depth of which varies according to the thickness of the weathered rock available. In the Himalayan hilly terrain groundwater development by open wells tapping the weathered residuum, cannot be done as groundwater moves away from the higher elevation to lower elevation very fast, resulting in the open well getting dry soon.

Ground Water Resources in West Bengal

The latest assessment made as on March 31, 2004, on the basis of GEC 1997 considering community development blocks as assessment units . Total annual groundwater recharge has been worked out as 30.36 bcm. Considering the natural discharge during non-monsoon period Net Ground Water availability is 27.46 bcm. Existing groundwater draft for irrigation and domestic uses are 10.84 and 0.81 bcm respectively (total draft 11.65 BCM). The stage of groundwater development of the state as a whole is 42%, indicating thereby a vast scope exists for further ground water extraction. All of the 515 blocks assessed are falling under "safe" category where stage of groundwater development remains within 70%. Based on stage of ground water development and long term pre and post monsoon water level trend , out of 269, there are 37 blocks have been categorized as Semi-critical and 1 no. of blocks as Critical . The rest of the blocks are under '**Safe**' category.

Issues Related to Ground Water Development

The various issues emerged during Ground Water Development in West Bengal are Chronically water scarce area in western part and in hilly tract in the northern part of the State, The area where depletion in water level has been ascertained, Hazards due to mining activity in Coal mine area and and Area falling under Geogenic contamination: High arsenic, High fluoride, High salinity and High iron

- Chronically water scarce area in western part and in hilly tract in the northern part of the State:

The districts of Purulia, western part of Bankura, Birbhum, Barddhaman, Paschim Medinipur face acute scarcity of water, mainly during the lean period due to limited yield potential of available aquifers. However, CGWB has identified potential deep fractures and successful bore wells have been handed over to State agency to augment their water supply system.

- Area where depletion in water level has been ascertained:

In KMC area, the piezometric surface in the Central Kolkata has been lowered to the tune of 5-9 m in the last 40 years forming a huge ground water trough due to withdrawal of ground water in excess of replenishment. Depth to piezometric level in the area varies from 3.34m to 16.32 m bgl in pre monsoon period and from 1.57m to 15.71m bgl in post monsoon period. Long term analysis of piezometric level data also shows a distinct falling trend of piezometric level in both pre and post monsoon period. A recent project of artificial recharge to deeper confined aquifer using roof top rainwater in KMC area (Baishnab-Ghata Patuli) has been proved to be very successful.

The Haldia Industrial Complex area falls in the coastal plains of West Bengal and fresh aquifers occur in the depth span of 120-300 mbgl. The piezometric level of the fresh ground water in the area lies within 7-15 m bgl. Study indicates that there is a distinct lowering of piezometric level of the fresh ground water to the tune of 5-7 m during last three decades due to heavy withdrawal of ground water from large no of heavy duty tube wells constructed by several organizations. As a result of this heavy withdrawal of fresh ground water, a ground water trough has been formed in the area close to the river Hugli. In order to avoid probability of sea water ingress into the aquifers, the same aquifers have been notified under CGWA to restrict withdrawal of ground water from the aquifers.

- Area falling under Geogenic contamination:

High arsenic in ground water:Arsenic contamination in ground water occurs in isolated patches in spreading over 79 blocks in eight districts namely, Malda, Murshidabad, Nadia, North 24 Paraganas, South 24- Paraganas to the east and Haora, Hoogly and Bardhaman to the west of Bhagirathi/ Hoogly river. Eastern part of Bhagirathi/ Hoogly river is much more affected than the western part. Deeper aquifers (> 100 mbgl) in the same area are generally free from arsenic. Ground water in arsenic affected area is characterized by high iron, calcium, magnesium, bicarbonate with low chloride, sulphate and fluoride.

High fluoride in ground water:The Task Force on Fluoride Contamination had recommended rapid assessment of fluoride concentration in ground water in 105 blocks of 12 districts of West Bengal. After the assessment, the final scenario regarding the high fluoride concentration in ground water of West Bengal has been observed in 43 blocks of 7 districts, namely Bankura, Birbhum, Purulia, Malda, Uttar Dinajpur, Dakshin Dinajpur and South 24 Parganas. However this problem is most serious in Bankura, Birbhum, Purulia and Dakshin Dinajpur districts. CGWB has found fluoride contamination above the permissible limit in Nadia and Bardhaman district as well. In the state highest concentration of fluoride in groundwater has been reported from Khyarasol block (15.9mg/lit) and Rampurhat-I block (17.9mg/lit) of Birbhum district.

High salinity:-Based on the geophysical surveys and ground water exploration, Brackish to saline and fresh water bearing aquifers have been deciphered in the different depth zones in Kolkata Municipal Corporation area, South 24 Parganas and in parts of North 24 Parganas, Haora and Purba Medinipur districts.

High iron in ground water:-Iron content in some isolated patches of Medinipur, Haora, Hugli and Bankura iron content is somewhat higher than 1 ppm and sometimes it exists more than 2 ppm in Haora and parts of Hugli districts. Likewise, in the Himalayan foothills in the districts of Darjeeling and Jalpaiguri ground water in near surface aquifers have iron as high as more than 3 ppm at places.

Conclusions

The highly diversified hydrogeologic settings and variations in the availability of ground water resources from one part of the country to other call for a holistic approach in evolving suitable management strategies. The emphasis on management needs does not imply that ground water resources in India are fully developed. Effective management of available ground water resources requires an integrated approach, combining both supply side and demand side measures.

There is a vast area in the Indo Gangetic alluvial plain where the ground water development is sub optimal and there is sufficient scope for future development. Similarly, urgent action is required to augment the ground water in the water stressed areas. However, focus on development activities must now be balanced by management mechanisms to achieve a sustainable utilization of ground water resources. Ground water constitutes the most important source of irrigation water in the Gangetic plains including the three states i.e. Bihar, Punjab and West Bengal. The productivity in terms of agricultural output is relatively low in Bihar and West Bengal as compared Punjab. Though, groundwater development for irrigation is feasible in these areas based on hydrogeological and environmental considerations , there is often a great economic barrier for the predominantly small and marginal farmers . A mechanisms have been developed or have emerged in these areas to enable farmers to benefit from ground water. Assured power supply is one of the key factors, the tariff, access and availability of which to a large extent determines the ground water use. Since the ground water development is mostly demand driven, it can be geared up through proper agricultural, credits, subsidy and energy support policies along with creation of suitable markets. In addition, the flood plains along the major river courses of the country offer good scope for groundwater development. Similarly, there are areas in the country with artesian condition, which can be mapped and suitable development plans formulated. In the alluvial areas, where multi-aquifer systems exist, there is a need to concretize methodologies for assessment of development potential of deeper aquifers. There is urgent an need for coordinated efforts from various Central and State Government agencies, non-Governmental and social service organizations, academic institutions and the stakeholders for evolving and implementing suitable ground water management strategies in the country.

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India's Ground Water Irrigation Economy: The Challenge of Balancing Livelihoods and Environment

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Abstract

Stagnating agriculture and consequent failure of rapid economic growth to bring about poverty reduction as envisaged have been major constraints for India's economic growth. Contrary to the view that slow-down in public investment for irrigation development is mainly responsible for the deceleration of agricultural growth, the paper argues that in spite of the Government initiatives and substantial investments in irrigation development, the area irrigated by public irrigation systems in India has stagnated or even declined. India's irrigation economy has been undergoing a dramatic transformation with the control of irrigation shifting from the government to the individual farmers through millions of wells owned and operated by them. Though the booming tube well irrigation has generated substantial socio-ecological dividends in terms of flood mitigation and reduction in water logging and soil salinization, it has also been responsible for resource depletion and contamination of ground water in some parts of the country, leading to various adverse environmental and socio-economic consequences. There is need for achieving the right balance between supply and demand side measures for forging a sustainable ground water governance regime. Problems of groundwater overexploitation in India are bound to become more acute and widespread in the years to come unless corrective mechanisms are put in place before the problem becomes insolvable or not worth solving. Lack of information and absence of systematic monitoring of availability and withdrawal of ground water is a major barrier that prevents the transition from groundwater development to management mode. Further, unlike in the case of surface water irrigation systems, public agencies have only an indirect role to play in the national ground water sector due to its development mostly in the private, 'informal' sector and the quality and amount of application of science and management to this sector has been much less when compared to the former.

This paper attempts to trace the history of irrigation development from early 19th century to the present to emphasize the shifting of focus from the government controlled major and medium surface irrigation systems to farmer-controlled ground water irrigation systems. Various ideas adopted for creating demand-management regimes through direct regulations, economic instruments, tradable property rights and community resource management around the world have been reviewed to prove the point that ground water governance, throughout the world, is still 'work in progress'. It also emphasizes the need for recognizing the importance of ground water irrigation systems in South Asia and for information systems and resource planning through establishing appropriate systems for regular ground water monitoring and for undertaking systematic scientific research on the occurrence, use and ways and means for augmenting and managing the resource. Need for initiating suitable demand and supply side management mechanisms and for undertaking ground water management in the river basin context have also been stressed.

Introduction

Stagnating agriculture has emerged, during recent years, as a speed breaker in India's otherwise splendid and enviable growth story. The failure of rapid economic growth to bring about poverty reduction in commensurate manner is also another major concern linked with stagnant agriculture. It has been widely thought that the slow down in public investment in agriculture, mainly irrigation development, is the main culprit behind the deceleration in agricultural growth. Government of India's Accelerated Irrigation Benefits Programme (AIBP) was conceived of as a response to the plea for increased public investment in irrigation. In recent budgets, the Union Finance Minister has been laying great stress on completing the "last mile irrigation projects" to step up the pace of irrigation development. Despite these initiatives, the area irrigated by public irrigation systems in India has stagnated, even declined (Shah 2009). In this paper, I want to argue that irrigation in India is in the throes of a major transition. The irrigation business model that India has followed since early decades of 19th century has rapidly changed in recent years, and public policies based on colonial model of irrigation development are no longer in sync with new developments in Indian agriculture, which has come to depend heavily on groundwater irrigation by boreholes and pumps. Neither the goals of India's irrigation policy nor our irrigation development strategy jives with the reality of our irrigation economy today. This transition has created a wholly new challenge of balancing food security and agrarian livelihoods on one hand and sustaining groundwater aquifers under stress. It brings into play a new socio-ecological dynamic that is best understood in the environmental economics framework.

Irrigation statistics compiled by the Government of India underestimate the scale of India's irrigation economy which is booming like never before. Official estimates of the net irrigated area in India based on land use surveys is 57 M ha and the gross irrigated area is around 90 M ha. Other sources, however, suggest that there is great deal more irrigation going on in India. The most striking have been new estimates of global irrigated area based on remote sensing data published recently by the International Water Management Institute (IWMI). Based on the analysis of high resolution satellite imagery backed by extensive ground-truthing work, IWMI's estimate suggests that in 2004, India had 99 M ha of net irrigated area and 132 M ha of gross irrigated area. Both these estimates are over 50 percent higher than the official estimates. In fact, IWMI's estimates of irrigated area of today are nearest to what the government of India would like to achieve by 2020. Incredible as these new estimates may sound, recent rounds of national sample survey also suggests that India's irrigation economy may be considerably larger than reflected in the official estimates.

The Groundwater Revolution

At the heart of the transformation that India's irrigation economy has been undergoing is the wresting, by millions of small farmers, of the initiative for irrigation development from the hands of the State. Under the model of irrigation development that India followed since the 1830's, the State has been the architect, entrepreneur, engineer and manager of irrigation systems. 'Command area' and 'duty' were the *mantra* of irrigation planning and management. The Government was the provider of irrigation and the farmer a passive recipient. In this model of unbalanced irrigation development, command areas were created near hydraulically opportune sites where reservoirs or weirs could be built and downstream areas could be 'commanded' by gravity flow. Farmers in the rest of the country were left to fend for themselves. Post-Independence, India followed much the same strategy for irrigation development that created pockets of prosperous command areas, leaving other parts to rain fed farming.

By 1970, the population pressure on farm lands in many parts of India had become so inexorable that farmers everywhere felt compelled to work their small farm holdings twice, or even thrice every year. Population pressure on farm lands then flagged off India's tube well revolution. India—especially, in western and north-western parts-- had a centuries old tradition of irrigating with wells. Even in 1900, India had some 4 M ha under groundwater irrigation. At the time of independence, the areas irrigated by groundwater and surface water were evenly balanced. However, it was hardly expected by anybody that India would witness massive spread of tube well irrigation in the surface-water-abundant Ganga-Brahmaputra basin or hard rock peninsular India. Such a pattern of irrigation development appeared wholly inconsistent with the country's hydro-geology. Equally inconsistent seemed to be large-scale groundwater irrigation in peninsular India with hard-rock aquifers that have poor infiltration and low storage; tanks have been considered ideal for capturing and storing rainwater for irrigation in these areas that comprise 65 percent of India's land-mass.

At the onset of the 20th century, RC Dutt articulated the prevailing thinking about how irrigation should develop in different parts of India. "Every province in India has its distinct irrigation requirements. In the alluvial basins of the Ganges and the Indus the most suitable irrigation works are canals from these rivers; while away from the rivers, wells are the most suitable. In Bengal with its copious rainfall, shallow ponds are the most suitable works and these were the numerous in the olden times, sometimes of very large dimensions. In Madras and Southern India, where the soil is undulating and the underlying rock retains the water, the most suitable irrigation works are reservoirs made by putting up large embankments and thus impounding the water descending from hill slopes. Such were the old reservoirs of Madras." (Dutt 1989, vol. II, p 119, footnote 1).

This thinking was endorsed 70 years later by the second Irrigation Commission. For millennia, irrigation in India had remained largely faithful to this dictum. Adaptive, minimalist, unobtrusive irrigation in India of 1800 was a reflection of this hydro-geologic make up of the sub-continental terrain. Constructive imperialism pioneered by Arthur Cotton in the south and Proby Cautley in the north took liberties with this ideal scheme. However, come 1970's, and this age-old wisdom lay in tatters as a new era of *atomistic irrigation* unfolded and engulfed India—nay, all of South Asia-- with small-pump irrigation spreading everywhere like wildfire --in canal commands and outside, in arid, semi-arid and humid areas, upstream *and* downstream of river basins, in excellent alluvial aquifers as well as in poor, hard rock peninsular aquifers with limited storage potential. If the era of 'constructive imperialism' began tinkering with the hydrology of river basins, the recent era of atomistic irrigation with small wells and tube wells went about reconfiguring it totally.

The rise of groundwater irrigation also transformed the organization of irrigation at the local level. In pre-Colonial India, co-operation at the community level was the dominant irrigation institution. Under the colonial rule, collaboration between the State and the engineering profession was at the centre-stage of centralized, bureaucratic irrigation development and management. In this new era of atomistic irrigation, the State as well as science became onlookers in a ballgame whose rules and logic they did not understand, much less dictate. In an incipient atomistic irrigation economy of the 1980's and later, neither the State nor the community was the entrepreneur, builder, or the manager of irrigation; it was the multitude of small-holders--Marx's 'millions of disconnected production units'--each with his tiny, captive irrigation system, ostensibly unconnected with the rest. Until now, crops had to wait for water to be released and flow through a network of canals before getting irrigated; now, water was scavenged on-demand and applied just-in-time when crops needed it most.

Between 1960 and 1985, India invested in irrigation projects many times more capital in real terms than the British had invested during the entire 110 year period between 1830 and 1940. Yet, even according to the government of India's figures, over 60 percent of irrigated areas are today served by groundwater. Other indicators suggest even this may be a serious underestimate. Remote sensing data as well as national sample survey suggest that as much as 75-80 percent of India's irrigated area today is served by groundwater wells. Until 1960, Indian farmers owned just a few tens of thousands of mechanical pumps using diesel or electricity to pump water; today India has over 20 million modern water extraction structures. Every fourth cultivator household has a tube well; and two of the remaining three use purchased irrigation service supplied by tube well owners.

Socio-economic significance and impacts of the groundwater boom

The groundwater boom is a sub-continental phenomenon that has encompassed, besides India, arid regions of Pakistan Punjab and Sind—which boast of the world's largest continuous surface irrigation system—and the humid Bangladesh and terai areas of Nepal. In these predominantly agrarian regions, the booming groundwater economies have assumed growing significance from viewpoints of livelihoods and food security; however, their significance as engines of rural and regional economic growth has remained under-studied. There are several ways to consider the scale of the groundwater economy; but one practical measure is the economic value of the groundwater production. An unpublished report for USAID in the early 1990's placed the contribution of groundwater irrigation to India's GDP at around 10 percent (Daines and Pawar, 1987); if that proportion held now, the size of the groundwater irrigation economy of India would be some US $ 75-80 billion. In table 1 below, we attempt a rough estimation of the market value of groundwater use in the Indian sub-continent. India, Pakistan, Bangladesh have active markets in pump irrigation service in which tube well owners sell groundwater irrigation to their neighbours at a price that exceeds their marginal cost of pumping. This price offers *a* market valuation of groundwater use in irrigation. We use available estimates of the number of irrigation wells and estimates from sample surveys on average yield of wells and annual hours of operation of irrigation tube wells in the countries covered. In India, for instance, a large number of farmers paid their neighbouring bore well owners US $ 0.04/m^3 for purchased groundwater irrigation around 2000; applying this price to the annual groundwater use of say 200 billion m^3 gives us US $ 8 billion as the economic value of groundwater used in Indian agriculture/year. For the Indian sub-continent, the corresponding estimate is around 10 billion US dollars. In many parts of water-scarce India, water buyers commonly enter into pump irrigation contracts offering as much as 1/3rd crop share to irrigation service provider; in water abundant areas, in contrast, purchased pump irrigation cost amounts generally to 15-18 percent of the gross value of output it supports. This can be used to draw the general inference that the agricultural output that groundwater irrigation supports is 4-5 times its market value.

Table 1 Proximate size of the Agricultural Groundwater Economy of South Asia (c. 2001-02)

		India	Pakistan Punjab	Banglad esh	Nepal Terai
A	Number of wells (million)	21	0.5	0.8	0.06
B	Average output/well (m3/hr)	25-27	100	30	30
C	Average hours of operation / well / year	360	1090	1300	205
D	Price of pump irrigation (US $/hr)	1-1.1	2	1.5	1.5
E	Groundwater used (km3)	189-204	54.5	31.2	0.37
F	Value of groundwater used/year in billion US $	7.6-8.3	1.1	1.6	0.02

Explosive growth in shallow tube wells and small pumps has democratized Indian irrigation much like personal computers have democratized computing globally. By the same token, large canal irrigation systems are heading towards the future that mainframe computers are facing. Boreholes and small pumps took irrigation away from command areas to the nook and corner of the country. Among several things, the booming pump irrigation economy has: [a] offered *some* irrigation access to an overwhelming majority, rather than concentrating *all* irrigation benefits on small privileged groups in command areas; [b] thereby, helped soften growing farmer unrest in the region's vast dry-land areas, which would have otherwise destabilized social and political structures; [c] has come to account for over 60 percent of irrigated areas, and 80 percent of irrigated farm output and resultant incomes; [d] drought-proofed the region's agriculture against at least one monsoon failure and made large-scale famines history; [e] improved farm wages and increased demand for farm labor year-round; [f] demonstrated a strong pro-poor, inclusive bias in irrigated agriculture; [g] supported a new drive towards intensive diversification to high value products such as milk, fruit and vegetables, especially in dry land areas in a scale-neutral format. These impacts have benefited—directly and indirectly, to lesser or greater extent--around half a billion rural people in South Asia. One can not say that the South Asian peasant is much better off in 2000 compared to 1975; but one can confidently say that, other things being the same, he would have been immensely worse off but for the pump irrigation boom.

Thanks to its myriad and widespread benefits, pump irrigation revolution, aided by irrigation service markets, has been amongst the most powerful rural poverty alleviation phenomena without which the region would arguably have been in the throes of massive social and political instability. Pump irrigation boom in India since 1975 has created more irrigation in 30 years than public investments in canal irrigation did in 170. Pump irrigation has also brought about greater spatial equality in irrigation; it is spread all over the country unlike canal projects which have created concentrated pockets of agrarian prosperity in canal commands. Vibrant local, informal markets for pump irrigation service have helped India's 20 odd million WEM owners to reach irrigation benefits to another 40-60 million small holder families, covering a vast majority of the farming community with access to supplemental irrigation. Especially in north-western India, the rise of groundwater irrigation on private initiative has reduced water logging, which otherwise would have required massive public investment in drainage and salinity management. The pump irrigation economy has been the driving force behind national growth in food and agricultural economies, for example, transforming West Bengal (and Bangladesh) as the region's rice bowls. Pump irrigation farmers apply less water per hectare, achieve higher ratio of evapotranspiration to consumptive fraction, and obtain higher yields/ha compared to flow irrigators. Across rural economic classes, the distribution of pump ownership is more equal than land holdings. In dry-land areas, supplemental pump irrigation has had a dramatic impact of stabilizing rain-fed yields and promoted agrarian diversification. The impact of a widespread drought on agricultural and food production today is much more muted compared to 1960's and before. Pump irrigation boom has been instrumental in all but banishing starvation deaths in the sub-continent. In effect, it has activated a sub-surface reservoir on a sub-continental scale—that always existed but remained largely unused—but which now captures and stores over 250-270 km^3 of water in a normal year, creating on a massive scale space, time and form utility in agricultural water use, the object of any reservoir.

Sustaining the Groundwater Boom

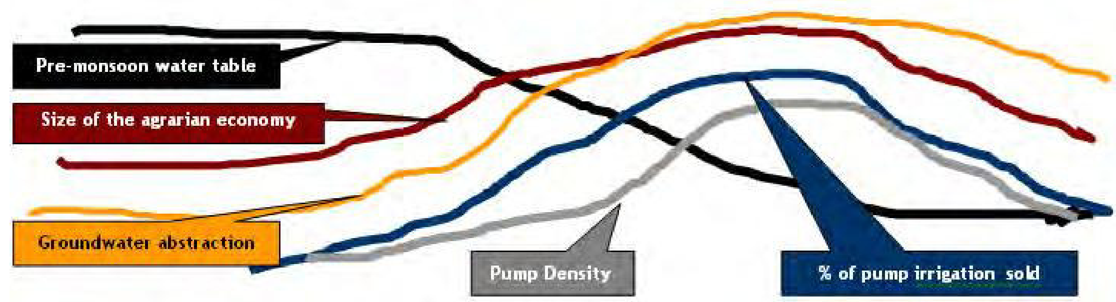
Nothing is an unmixed blessing; and this is true about South Asia's pump irrigation revolution since 1970's which has been a prominent target of doomsday prophecies about an impending socio-ecological disaster (see, e.g., Seckler et al.1999; Postel 1999; Vaidyanathan 1996). There is much truth in this concern; however, tube well irrigation has generated substantial socio-ecological dividends as well. In flood prone eastern India, it has helped mitigate the rapacity of floods and water logging by reducing 'rejected recharge' by creating more storage in the aquifers. In the Indus basin too, tube well irrigation has reduced water logging and salinization, a task which would have taken hundreds of million dollars of investments in drainage.

Groundwater horror stories of India are however becoming increasingly frightening in arid alluvial and hard-rock aquifers. In some coastal plains along with arid alluvial plains facing overdraft, the central resource governance challenge is coping with salinization and depletion which, in a chronic form already visible in some parts, may seal the fate of agriculture, and of human settlement itself. Then, in hard rock areas of peninsular India, where tube well irrigation expansion is way out of proportion to the limited storage offered by aquifers, resource depletion is a serious issue in itself but has also aided growing concentration of fluoride and other salts in groundwater which is the main source of drinking water supply for rural as well as urban populations. Problems of geogenic contamination of groundwater—such as with arsenic in eastern Ganga basin and fluoride in much western and peninsular India are large and serious. The causal role of pump irrigation in mobilizing fluoride and other salts in groundwater is clearer than in arsenic contamination whose chemistry is still tenuous and disputed.

A few years ago, David Seckler wrote alarmingly that a quarter of India's food harvest is at risk if she fails to manage her groundwater properly. Many people today think that Seckler's may well have been an underestimate; and that if India does not take charge of her groundwater, its agricultural economy may crash. Sandra Postel (1999) has suggested that some 10 percent of the world's food production depends on overdraft of groundwater to the extent of 200 km^3; most likely, 100 km^3 out of this occurs in Western India. Conditions in North China plains they are no better. In the lower Indus basin in Pakistan and the Bhakra system in Northern India, groundwater depletion is not a problem but soil and groundwater salinization is. IWMI's past research to understand the dynamics of groundwater socio-ecologies indicates some recurring patterns. In much of South Asia, for example, the rise and fall of local groundwater economies follow a 4-stage progression outlined in Figure 1 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 1 shows the transition that South Asian policymakers and managers need to make from a resource *development* mindset to a resource *management* mode. 40 years of Green Revolution and mechanized tube well technology have nudged many regions of South Asia into stage 2-4. However, even today, there are pockets that exhibit characteristics of stage 1. But the areas of South 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. An oft cited case 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 barely a decade ago. This drama is being re-enacted in ecology after groundwater socio-ecology with frightful regularity (Moench 1994; Shah 1993; Barry and Issoufaly 2002).

Figure 1 Rise and fall of groundwater socio-ecologies

	Stage 1	Stage 2	Stage 3	Stage 4
Stages	The rise of Green Revolution and Tube well Technologies	Groundwater-based Agrarian Boom	Early Symptoms Groundwater Over-draft/Degradation	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 tube wells; 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; agri. 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 tube well 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 can not 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.

In stage 1 and early times of stage 2, the prime concern is to promote profitable use of a 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. 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. IWMI's recent work in North China plains suggests that the story is much the same there as well. The critical issue to address is: does stage 4 always have to play out the way it has in the past? Or, are there adaptive policy and management responses in stage 2 that can generate a steady-state equilibrium, which sustains the groundwater-induced agrarian boom without degrading the resource itself? In the remainder of this paper, we review the prospects and opportunities for forging such a steady-state equilibrium.

Environmental Economics of Aquifers and Institutional Response

Groundwater modeling is the playing field for hydro-geologists. These have developed a rather formidable repertoire of models that analyze the complex behavior of aquifers in response to development. However, in a region like South Asia where millions of smallholders directly interfere with the aquifer processes without let or hindrance, we have little understanding of how users respond to its development, and in due course, its depletion or deterioration. Developing such understanding is an important area of work for environmental economists.

How do India's groundwater users relate to aquifer development? How do they respond, as individuals and as a collectivity sharing a portion of an aquifer, to groundwater depletion or quality deterioration? When do they choose to co-operate and when to compete? Do they actually choose? Or are they impelled to behave in a certain way by natural processes they are confronted with? Are there situations in which they find it easier than in others to co-operate for the greater common good? These, and many other such questions, are crucial for us to explore but require a marriage of hydro-geology and social sciences such as economics, political science, and sociology.

Much hydrogeology is about the impact of human intervention on aquifer behavior. But environmental economics also needs to explore the impact of aquifer conditions on human behavior, especially, the behavioral response of people living off it. By institutional response, I mean the central behavioral tendencies of groundwater irrigators and the social dynamic that results from different aquifer conditions. In keeping with Veblen (1934), the original institutionalist, I treat institutions as 'settled habits of thought common to the generality of men'.

An average groundwater user in India has little or no *formal* knowledge of hydro-geology. But s/he certainly has ideas and even theories about how it all works underneath the earth's crust (Rosin 1993; Shah 2000). A lot of these popular theories will not withstand scientific scrutiny; yet, farmers' decisions and actions are guided by *their* theories more than by formal science. One way to think about how farmers form their theories is by referring to what economist John Muth (1961) called rational expectations which help people formulate their view of the future state of things. Rational expectations are to be distinguished from *adaptive* expectations, which see the future as little more than a mechanical reproduction of the past. The *rational expectations model* suggests that people take into account all the information available to them—including the expectations of others they regard highly--to arrive at an expectation which differs from the actual only by a random error (Muth 1961; Sargent 2002). When the behavior of most or all agents is shaped by such rational expectations, self-fulfilling prophecies abound. If majority customers expect a bank to fail, and begin a run on it, a small bank may actually fail. If most traders expect stock prices to rise, and start buying in that expectation, the market will actually skyrocket even when fundamentals suggest no reason for it to. Likewise, the expectations people living on or off an aquifer have about where it is headed in response to development or conservation shape their individual or collective behavior towards it and towards the 'aquifer community'.

An 'aquifer community' can be viewed as a collectivity of aquifer users in a locality who are aware of their interdependence in their use of a common aquifer or a portion thereof. Researchers from the British Geological Survey (2004) put it elegantly when they define it as a group of groundwater users who are 'mutually vulnerable and mutually dependent because of the centrality of resource use in supporting livelihoods'. The level of awareness of this inter-dependence is a measure of the strength or weakness of the aquifer community. In understanding the institutional dynamic in an aquifer, important are the rational expectations that a representative farmer has about the impact of another farmer's withdrawal on own water availability (**s**), and of the whole community's withdrawals on her groundwater availability (**S**); individual farmer's water conservation effort on her water availability (**h**) and the community's conservation effort on her water availability (**H**). Five situations outlined in table 2 represent the types of institutional dynamic that aquifer conditions generate in response to development in South Asia.

[**Situation 1**] ***atomistic individualism*** ***($s=0$; $S=0$; $h=0$; $H=0$)***: occurs when each farmer is an insignificant user in an abundantly recharged water table aquifer; his abstraction has little impact on himself or other users; likewise, aquifer development has little discernible impact on the individual user; here, interdependence amongst users goes unnoticed; 'aquifer community' is non-existent, and rational expectations fail to generate institutional dynamic of the kind we observe in the remaining four situations;

[**Situation 2**] ***collusive opportunism*** ***($s=0$; $S<0$; $h=0$; $H=0$):*** occurs when aquifer development sharply raises the cost of groundwater abstraction without greatly reducing water supply or quality; here, wealthy farmers establish de facto control over the resource, and collude against the resource poor but spearhead political mobilization to defend their access to and control over the resource; irrigators display limited inter-dependence and are a weak aquifer community;

[**Situation 3**] ***rivalrous gaming*** ***($s<0$; $S \ll 0$; $h=0$; $H>0$):*** occurs when aquifer development sharply raises the cost of water production and also limits available groundwater supply that users actively compete for; this condition promotes intense and destructive rivalry among competing users; irrigators display a strong sense of interdependence but are a dysfunctional aquifer community; sporadic evidence of beneficial effects of community conservation fail to metamorphose into organized collective action;

[**Situation 4**] ***co-operative gaming*** ***($s<0$; $S \ll 0$; $h>0$; $H \gg 0$):*** under certain catalytic conditions, rivalrous game metamorphoses into a co-operative game that reduces the cost and risk of water production and augments water availability to the entire community; positive expectations that so result foster a strong sense of benign interdependence and a highly functional aquifer community; such aquifer communities are ripe for proactive local groundwater self-governance;

[**Situation 5**] ***exit*** ***($s \ll 0$; $S \ll 0$; $h=0$; $H=0$):*** This state occurs when groundwater development results in rapid quality deterioration without affecting supply. Costs and risks of groundwater use become prohibitive; and users begin giving up irrigated farming or farming itself. Pervasive negative expectations inspire fatalism, hopelessness and despair that overwhelm the strong sense of interdependence; aquifer community takes a downward spin and eventually withers away.

The framework set out above is helpful in making sense out of how millions of farmers have responded to the ecological consequences of rapid groundwater development in different parts of India. In alluvial aquifers of arid western Rajasthan and North Gujarat, groundwater irrigators are running a race to the 'pump house'; competitive deepening of tube wells is the name of the game here. In these regions, we never hear about spontaneous efforts by farming communities to harvest rainwater and recharge aquifers on a large scale; the predominant institutional response takes the form of mobilizing to maximize and preserve energy subsidies. In humid alluvial plains of the Ganga-Brahmaputra-Meghana basin, groundwater irrigation here is a major poverty-alleviator and poses no environmental threat. Yet it is rapidly shrinking in the face of a stringent energy squeeze; and small farmers here are unable to organize and mobilize political power to save their livelihoods. Most large-scale mass-based groundwater recharge initiatives are concentrated in hard-rock areas; here, well owners compete fiercely to maximize their share in available groundwater resource but can be organized in a co-operative game to augment the resource and regulate the abstraction. In fragile coastal aquifers, the ecological fall-out of rapid and unregulated expansion in groundwater abstraction are swift and disastrous, leaving 'exit' from irrigated farming as the dominant option.

Table 2 Patterns of institutional responses to aquifer development in India

Institu-tional response situation	Aquifer characteristic	Impact of aquifer development on typical user	Pump irrigation markets	Example	Ease of political mobilization of farmers	Scope for Local aquifer governance
Atomistic individualism	High storage; high recharge resources	Insignificant	Efficient, deep and broad; WEM ownership a major source of neither power nor profit.	Most of Indo-Gangetic basin; alluvial canal commands	Low	Nil
Collusive Opportunism	High storage; no or limited recharge resources	Sharply rising marginal cost of groundwater	Highly monopolistic, fairly deep and broad; resource poor elbowed out of pump irrigation economy	North Gujarat; Western Rajasthan	High for energy subsidies and surface water imports	Low or nil
Rivalrous gaming	Hard-rock aquifer with low aquifer storage; some recharge resources	Rising marginal cost and declining share in limited water	Highly monopolistic; thin and shallow; poor have limited access at adverse terms	Inland peninsular India; Baluchistan	High for energy subsidies and recharge resources;	Scope for functional aquifer community
Cooperative gaming	Alluvial with a confining layer or humid hard-rock environment with low storage;	Sharply rising marginal cost and declining share in limited water	Monopolistic; moderate in depth and breadth; access to groundwater more equitable	Eastern Rajasthan; coastal Saurashtra;	High for energy subsidies and recharge resources;	High; functional aquifer community
Exit	Fragile aquifers prone to rapid quality deterioration	Sharp deterioration of water quality	Absent or insignificant	Coastal aquifers in Saurashtra; fresh water lenses in Sind	Low	Nil

In search of sustainability

In thinking about forging a sustainable groundwater governance regime, the emerging global consensus is for achieving the right balance between supply and demand side measures. Governments can meet groundwater depletion in a locale by investing in recharge and/or water imports. However, without effective demand-side measures, increased supply will quickly invite increased abstraction, leaving the resource depleted. In creating demand management regimes, four sets of ideas have been tried worldwide: direct regulation, economic instruments, tradable property rights, community resource management. These are reviewed briefly; but the interesting upshot of this discussion is that throughout the world, groundwater governance is still work in progress.

Direct regulation through administrative action:

State claiming eminent domain and using the administrative apparatus of the government to regulate groundwater abstraction dominates the GwG regime in many countries, notably the Sultanate of Oman, Iran, Saudi Arabia, Israel and of course the western United States. In South Asia too, groundwater departments in most Indian states as well as Bangladesh have norms for siting irrigation wells and the minimum spacing to be maintained to minimize well-interference externalities. India has a draft groundwater law tossing around now for over 30 years; several state governments have passed groundwater laws providing regulatory powers (Planning Commission 2007). The regulatory effectiveness of these however has remained limited for a variety of reasons, the chief being the lack of popular support, political will and enforcement capacity commensurate with the enforcement challenge.

Countries like Oman, Saudi Arabia, Jordan and Iran however have used this instrument with greater vigor and seriousness. The hallmark of Oman's GwG regime is the strong and very visible hand of the state. The experience everywhere has been mixed, in fact quite poor, as was concluded by a conference of MENA countries in 2000 (World Bank and Swiss Agency for International Development 2000:18). Elsewhere, even talk about regulation has generated a groundswell of opportunistic response from farmers. In Mexico, the political leaders have been issuing, from time to time since 1949, 'regularization' deadlines after which new tube wells would be banned in stressed aquifers. Every time, however, the threat has invariably invoked a tube well-boring spree (Scott et al. 2003). The last time the 'deadline' was issued in 1997, the tube well numbers doubled in the central Mexican province of Guanahuato (ibid). A leading Mexican practitioner of GwG concluded regulation would not work 'unless social and economic realities are taken into account' (Sandoval 2004).

Direct regulation of groundwater users through law is by far the most talked-about intervention in India. A model groundwater bill was formulated during the early 1970's and revised versions have been tossed around since then. Since water is a state subject in India, the action lies with state governments; and few showed interest in formulating a groundwater law; and even fewer in enforcing it. The key problem is the transaction costs of enforcing such a law on millions of scattered borehole owners in the countryside. As the following table 3 shows, the organization of groundwater economy is a major determinant of what kind of regulatory action is appropriate. India withdraws twice as much groundwater as does the US but would have to enforce a groundwater law on 100 times more irrigators.

Table 3: Structure of national groundwater economies of selected countries

Country	Annual groundwater use (km3)	No of Agricultural Groundwater Structures (million)	Average extraction/ structure (m3/year)	% of population dependent directly or indirectly on groundwater irrigation	Average farming income per farm worker
India	210	19	7900	55-60	~350
Pakistan	55	0.5	90000	60-65	~400
China	105	3.5	21500	22-25	~458
Iran	29	0.5	58000	12-18	~2200
Mexico	29	0.07	414285	5-6	3758
USA	100	0.2	500,000	<1-2	67800

Economic Instruments:

Economic instruments are attractive because they can influence the behavior of numerous economic agents without having to coerce or invoke eminent domain. Using a price or a Pigovian tax or cess is basic economic instrument to signal scarcity value. The problem in pricing groundwater is often the high transaction costs of metering, monitoring and charge collection; as a result, pricing is effectively used when it can be levied on bulk users or service providers who can transmit the 'price signals' onward to users. In Western United States, 'pump tax', generally higher for industries than for agricultural users, was widely used to control groundwater overdraft (Turral 1998). In China, water pricing—for cost recovery as well as demand management in cities—has worked because municipalities collect them from a handful of water service providing companies; however, collecting water withdrawal fees, provided by the 1995 Water Law, from millions of scattered agricultural tube well owners has proved far more challenging (Shah et al. 2004a). In her new Law of the Nation's Waters, Mexico, like China, has provided water resource fees—besides service charges-- to be levied on all users including irrigators.. However, like with China, Mexico too has found its implementation difficult (Shah et al. 2004b).The best known case of water pricing for agricultural use is Israel where all irrigation diversion and delivery points are metered and closely monitored (Feitelson 2006). Jordan has introduced a groundwater abstraction charge for industrial users; but its extension to agriculture invited much resistance. Jordan had to use force in installing meters on deep tube wells and create 'quasi water police' to enforce pumping quotas (World Bank and the Swiss Agency for Development Co-operation 2000).

There has been greater success when pricing is used to create incentives for moving water to higher value uses. Saudi Arabia and Yemen have tried paying farmers to sell groundwater to towns than using it for irrigation (Abderrahman 2003; Briscoe 1999). In India, Metro-water, the water service provider of the city of Chennai, too has been able to do this successfully. In the industrialized world, compensating farmers to reduce negative third-party externality is common. Some German cities have been paying peri-urban farmers to reduce chemical use in their farming to reduce non-point pollution of groundwater (Shah, Molden, Sakthivadivel and Seckler 2001); and in the western US, it is common for cities to buy up groundwater rights from farmers or for the federal government to pay groundwater irrigators in over-drafted areas to switch to dry-land farming. Direct scarcity pricing of groundwater use in irrigation in developing countries is, however, rare, not because the principle is in doubt but its actual practice has proved difficult.

Tradable Property Rights:

The conceptual foundation of the tradable property right discussion rests on the premise that under open access, groundwater resource would always be open to depletion and degradation. One road to sustainable resource management is of creating enforceable private property rights, preferably tradable. Tradable water rights modify the outlook of the users as well as third-parties about externalities, leading to more efficient allocation—though not necessarily conservation—of the resource. The historical foundation of tradable rights, however, rests in the history of European settlements in the New World, where secure property rights were essential to attract settlers to make private investments in land and water development. The idea of the groundwater governance regimes in the US and Australia then rests on the worldview that users *can* evolve mechanisms for self-governance of the resource with the state providing an overarching regulatory and facilitative framework. The actual experience with such collective self-governance is a matter of much debate even within these countries; however, their experience has given birth to a growth industry for promoting tradable water rights as a one-stop solution to groundwater mal-governance. Virtues of tradable property rights are widely advertised and commended (Rosegrant and Gazmuri 1994). The outcome of an innovative project of introducing tradable water rights in Chile has been vigorously lauded (ibid) as well as roundly criticized (Bauer 2004; Boelens and Bustamante 2005; GWP, 2006).

At the conceptual plane, there is little to gainsay the hypothesis that tradable property rights result in superior allocation of scarce water. The real problem in using this approach effectively in countries like India, however, is the transaction costs, which rise in geometric progression with the increase in the number of users. While the property rights protagonists have not paid much heed to transaction costs, these were central in the scheme of Ronald Coase, the original master, who warned that the assignment of property rights would be of little avail: [a] if the information available to contracting parties were less than perfect, [b] if transactions costs were high, and [c] if the number of contracting parties was too large to permit easy negotiations amongst them. As Armen Alchian, another prominent property rights theorist, similarly argued,

"The cost of establishing private property rights—so that I could pay you a mutually agreeable price to pollute your air—may be too expensive. Air, underground water, and electromagnetic radiations, for example, are expensive to monitor and control… When private property rights are unavailable or too costly to establish and enforce, substitute means of control are sought. Government authority, expressed by government agents, is one very common such means."

Even where transactions costs are manageable, results are not uniformly satisfactory. Fertile ground for studying the impacts of a variety of tradable water rights regimes is the Western United States. In some states like Kansas and Colorado, groundwater management is centrally about proactive demand management and of third-party externalities generating massive amount of litigation and supporting an army of water lawyers. A contrasting view, however, is that in a state like Texas, which has embraced the 'rule of capture', the situation can be nearly as anarchic as in South Asia. Even where the resource is threatened, demand management by reducing irrigated areas or groundwater withdrawals through rights administration is more an exception than a rule. When groundwater pumping is restricted to meet a threat to the aquifers, it is often because new water supply is offered in lieu of pumping of groundwater or because soaring pumping cost makes groundwater irrigation economically unviable.

According to Henry Vaux, a senior economist from the University of California at Berkeley, out of 431 groundwater basins in California, only 19 are 'actively managed', implying some restrictions on pumping. In all the rest, groundwater management is passive, basically involving federal government grants to build infrastructure to import surface water and supply it to groundwater users in lieu of pumping. Here, nobody is expected to reduce groundwater use. Vaux also suggests that active management basins are generally overlain by highly urbanized areas where governments or municipalities can easily buy water rights to serve high paying urban consumers. US Groundwater Management Districts are held out as a model of collective action in which members make and enforce norms on reducing abstractions; however, such is seldom the case. In his celebrated study of local resource management in eight groundwater basins in California, the collective action that Blomquist studied is mostly about implementing supply side interventions, much like the Indian farmer communities have evolved in hard rock areas of Saurashtra and Eastern Rajasthan.

All in all, it is by no means clear that the rich institutional and regulatory activity the western and central US has experienced has been uniformly helpful in creating a wholesome GwG regime. The Ogallala aquifer continues to be depleted; Kansas experiences "widespread falls in groundwater level of significant magnitude [that are] non-recoverable in large areas' (Kalf and Woolley 2005). In Arizona, over-exploitation and falling water levels are addressed by legislation that mandates balancing abstraction with recharge; but it is 'not clear that targets will be met" (Kalf and Woolley 2005). In California, courts have determined 'equitable distribution' over large areas; but Kalf and Woolley (2005) think 'it may not lead to sustainable use'. In Texas, James Nachbaur, who studied groundwater governance there, found irrigation interests always defeated laws designed to regulate them (Shah 2006). Allen (in Giordano and Villhoth 2007:75) suggests: 'Even in economies that had the political and economic space to pursue knowledge-based groundwater management policies, both renewable and non-renewable aquifers have been seriously depleted. Overuse of the aquifers of the High Plains of Texas is a sorry tale." The US experience inspires little faith in demand management; its lesson is that the practical way to protect a stressed aquifer is to ease pressure on it by developing alternative supply sources. That done, try what demand management you can do.

As an interesting aside, groundwater institutions in the US and Australia tend to be highly sensitive to transaction costs. This is why they are careful to 'exempt' numerous relatively small –*de minimis*—users from the GwG regime which has to contend only with a small number of large users. Kansas thus exempts *de minimis* users who divert up to 15 acre feet of groundwater. In Nebraska, only wells that pump 50 gallons or more per minute need a permit, a meter and an allocation (Nagaraj et al 2000). In Australia too, those irrigating up to 2 ha are exempted as *de minimis* users (Macdonald and Young 2000:24). An extreme case of transaction-cost minimizing groundwater governance regime is chosen by states like Texas that have deliberately embraced groundwater anarchy by adopting the principle 'let the locals figure it out for themselves'. If India and China were to undertake institutional management of the Colorado and Kansas kind, the resources they would need, in terms of money and manpower, would be humongous, indeed. And if they were to exempt *de minimis* users by Kansas, Nebraska and Australian standards, over 95 percent of users would fall through the regulatory sieve.

Community Aquifer Management

In evolving their groundwater governance regimes, Mexico and Spain have adapted the US experience of tradable water rights and Groundwater Management Districts. The underlying premise—somewhat along the Coasean logic-- is that if groundwater users are organized around aquifers for self-governance, they will internalize third-party externalities through bargaining and negotiation, collectively monitor the behaviour of groundwater as well as its abstracters, and ensure the long term sustainability of both. A more practical consideration was to use groundwater associations as agents in monitoring and enforcement of government policies and laws. The idea of groundwater organizations has a wide appeal; it was advocated to India by a British Geological Survey study (BGS 2004). And in south India, the FAO supported Andhra Pradesh Farmer Managed Groundwater Systems Project has organized groundwater users in 650 habitations in 66 hydrological units (Knegt and Vincent. 2001). Spain and Mexico have however embraced groundwater organizations as key element of their official national water governance strategy.

Until 1985, Spain, like Texas, followed the rule of capture. However, the intensification of groundwater stress under unregulated agricultural use prompted stern measures. The 1985 Water Act nationalized groundwater, and prescribed River Basin Management Agencies (*Confederacions Hidrograficas*) with an active role in managing groundwater. These were vested with the power to grant permits for groundwater use, declare an aquifer as overexploited, and formulate an aquifer management plan for its recovery. These typically involved reduction in the volume of withdrawals by rights holders and rejection of new applications for wells. To encourage user participation, all users of the aquifer were organized into groundwater user associations.

An assessment of the results of groundwater reforms in Spain by Spanish researchers suggests a rather gloomy picture. For one, even after 20 years, recording of groundwater rights still remains incomplete; worse, less than a quarter of all groundwater structures have been registered. Intensive groundwater governance does not come cheap; recording rights and monitoring them requires far more human and other resources than are available at the disposal of the implementing agency. Thus, Spain, with some 0.5 million irrigation wells, is still grappling with the most basic issue of identifying and recording groundwater users. Given Spain's long tradition of successful surface-water users associations (some in Valencia are centuries old), the new water law hoped similar associations would do the trick for groundwater aquifers as well. Thus, while thousands of small groundwater user associations have been 'registered' on paper, only a handful have made some movement towards `collective management of aquifers' and even fewer have met with some success. Even Spanish researchers were disappointed. Villaroya and Aldwell (1998) concluded "In Spain, [groundwater] overexploitation is dealt with in the water act and implemented by the regulations that enforce that act. Experience has shown that without the cooperation of the water users themselves, good results are not obtained."

Concessions have created a new dynamic of opportunism. Recently, the CNA announced its intention to withdraw unused portions of groundwater quotas; this generated a perverse 'use-it-or-lose-it' feeling among farmers. Luis Marin, a Mexican researcher, reported, "In Mexico, the government has tried to give the stakeholders the responsibility for managing aquifers by establishing COTAS. However, COTAS depend financially on subsidies from… governments… Under the new law, stakeholders who don't use all of the volume that they have a permit for, stand to lose the unused volume the following year. As a result, stake holders extract their full volumes, even if much of this water is wasted, only not to have their concessions reduced." (Personal communication by e-mail of 7 July, 2005).

Enacting and enforcing a groundwater law, establishing clear tradable property rights on water, pricing groundwater as an economic good, installing and enforcing a licensing and permit system—all these have been discussed *ad nauseum* as desirable policy interventions to regulate groundwater overdraft (see, e.g., Arriens et al 1996: 176-178; 239-245). Nobody seems to disagree with the need for these; yet, no Asian country has been able to deploy any of these interventions effectively even as the groundwater situation has been turning rapidly from bad to worse. The scale of the groundwater threat is long recognized; but viable strategies for dealing with it are not forthcoming; indeed, governments are still busy promoting more groundwater development, as if they were in Stage 1.

Indirect levers

Because of our large number of small, scattered groundwater abstractors, India would need to devise its own groundwater governance strategy that fits with her context. There are potentially powerful *indirect* demand-management strategies that are not even part of the academic discussion on groundwater management in the developing world. These offer important trade-offs that need closer scrutiny. For example, it has been suggested that the Indian Punjab's groundwater depletion problems could be easier to resolve if its export of 'virtual' groundwater in the form of rice could be reduced or stopped; on the other hand, IWMI researchers have suggested that, in North Indian plains, using earthen canals for recharging with flood waters of monsoon rains can help counter groundwater depletion (IWMI-Tata Water Policy Briefing 1). Water- saving irrigation research—such as Alternate Wet and Dry Irrigation (AWADI) for rice in China or the System of Rice Intensification which has found enthusiastic following in scores of countries including India and Sri Lanka (Satyanarayana, 2005 and Sinha and Talati 2007)—can help reduce groundwater use; but it needs to be examined if these technologies would work as well in dry areas. In many developing countries, pricing and supply of electricity to tube well owners can offer powerful levers for agricultural demand management for groundwater. Since levying a price on groundwater itself may entail high transaction costs of collection, energy price can serve as a useful 'surrogate' (Shah et al 2004c; Scott and Shah 2004).

Another key are to work upon in South Asia, especially India, are the perverse energy subsidies for tube well irrigation. In the populous South Asian region, there seem no practical means for direct management of groundwater; laws are unlikely to check the chaotic race to extract groundwater because of the logistical problems of regulating a large number of small, dispersed users; water pricing and/or property right reforms too will not work for the same reasons. However, electricity supply and pricing policy offers a powerful toolkit for *indirect* management of both groundwater and energy use. Since electricity subsidies have long been used by governments in this region to stimulate groundwater irrigation, the fortunes of groundwater and energy economies are closely tied.

India is a classic example. Today, India's farmers use subsidized energy worth some US $ 4.5-5 billion/year to pump some 150 km^3 of water mostly for irrigation; the country's groundwater economy has boomed by bleeding the energy economy. With electricity industry getting close to bankruptcy, there are growing demands for eliminating power subsidies; but governments find it unable to do so because of stiff opposition from farmer lobby. Recent IWMI research (Shah et al 2004) has argued that sustaining a prosperous groundwater economy with viable power sector is feasible but it requires that the decision makers in the two sectors jointly explore superior options for energy-groundwater co-management. IWMI studies recognize that switching to volumetric electricity pricing may not be politically feasible at present. However, they advocate flat tariff accompanied by sophisticated management of high quality but carefully rationed power supply to maintain at once the financial sustainability of energy use in agriculture and the environmental sustainability of groundwater irrigation; and has argued that such a strategy can curtail wasteful use of groundwater in irrigation to the extent of 15-18 km^3/year.

Transition Needed: From Resource Development to Management Mode

In the business-as-usual scenario, problems of groundwater over-exploitation in India 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 five important steps:

1. Recognizing that even as the bulk of the public policy and investments are directed at large government managed irrigation programs, in reality, South Asia's agriculture has come increasingly to depend upon small-holder irrigation based largely on groundwater; policy effort as well as resource investments need to adjust to this reality if these are to achieve *integrated* water and land resources management in the true sense;
2. Information Systems and Resource Planning through establishing appropriate systems for groundwater monitoring on a regular basis and undertaking systematic and scientific research on the occurrence, use and ways of augmenting and managing the resource;
3. Initiating some form of demand-side Management through [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 of surface and groundwater by reinventing main system management processes to fit a situation of intensive tube well irrigation in command areas; [e] promotion of 'precision' irrigation and water-saving crop production technologies and approaches;
4. Initiating Supply-side Management through: [a] promoting 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; and finally,
5. Undertaking Groundwater Management in the river basin context. 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. A rare example 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. The actual equity effects of shared management by Israeli's and Palestinians here are open to controversy, however, this offers an early example of issues that crop up in managing trans-boundary aquifers (Feitelson and Haddad 1998). Equally instructive for the developing world will be the impact of the entry of big-time corporate players 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 Asia learns intelligently from these ideas and adapts them appropriately to its unique situation.

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Sustainable Groundwater Development through Integrated Watershed Management for Food Security

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Abstract

Globally rain-fed agriculture is playing and will continue to play an important role for food security and sustainable agricultural development (Wani et al. 2008, 2009, Rockström et al. 2007). Rainwater is the main source of water for agriculture but its current use efficiency for crop production is low (30-45%). The Comprehensive Assessment of Water Management in Agriculture for Food and Health has discarded the artificial divide between the irrigated and rain-fed agriculture as none of these systems exist in isolation but are in a continuum from rainfed – rainfed with supplemental irrigation to fully irrigated systems (Molden et al. 2007). Groundwater is an important source for irrigated agriculture as it generally furnishes reliable and flexible inputs of water. To this extent, groundwater is instrumental in managing risk and optimizing food production in the rainfed areas. However, this reliance upon shallow aquifer systems for irrigation has turned to dependency. Depleting groundwater is a serious problem throughout Asia and more so in India as more than 22 million wells are operational in India supporting the economy.

Integrated watershed development is the strategy adopted in the country for sustainable development of dry land areas and a recent comprehensive assessment of watershed programs in India undertaken by ICRISAT-led consortium revealed that integrated watershed can become the growth engine for sustainable development of dry land areas by improving the performance of 2/3rd watersheds in the country (Wani et al. 2008). In most of the developed watersheds with concerted efforts to manage rainwater, the groundwater availability is improved not only in the watershed, but the downstream areas also benefited with increased groundwater recharge (Wani et al. 2003, Sreedevi et al. 2006, Pathak et al. 2007). Along with the increased surface and groundwater availability and concomitant private investments also substantially increased in the developed watersheds, resulting in the increased incomes as well as improved livelihoods (Sreedevi et al. 2006, 2008 and Pathak et al. 2007). Increased water availability also had a positive impact in improving welfare for the women, reduced drudgery, and protected the environment. In few well-managed watersheds, the productivity per unit of land and water increased substantially (Wani et al. 2003). However, agricultural production increased in many watersheds, the productivity per unit of land and water was not increased (Sreedevi et al. 2006). There is a need to adopt more water use efficiency measures along with integrated management of water resources in watersheds for sustaining the development measures. There are a number of examples where with the watershed development based on the over-exploitation of groundwater by the community, depleted groundwater to levels lower than those before the watershed development. Increased numbers of wells (open and bore wells) along with the increased number of pumping hours pose a serous threat for sustaining the development in the watersheds. The results from the watershed case studies from Andhra Pradesh, Madhya Pradesh, Rajasthan, Maharashtra and Gujarat are used to derive the conclusions (Batchelor C et al. 2000).

In the various watersheds of India like Lalatora in Madhya Pradesh, the treated area registered a groundwater level rise by 7.3 m. At Bundi in Rajasthan, the average rise was 5.7 m, and the irrigated area increased from 207 ha to 343 ha. In the Kothapally watershed, the groundwater level in open wells rose by 4.2 m. In the Rajasamadhiyala watershed, the number of open wells increased from 255 in 1995, with very poor yield with an average water column of 5.9 m to 308 wells with mean water column of 10.4 m. Overall, there has been an increase of 4.4 m of water column in 2004, as compared to that of 1995. The average pumping duration of 5.25 hrs per day in 1995 increased to 10.4 hrs per day in 2004, resulting in increased irrigated area by 58 per cent. Similarly, the number of bore wells also increased from 102 to 200 during the period. Doubling of the number of the bore wells in the watershed is a cause of concern as in spite of farmers' experience of defunct bore wells in 1995 and *earlier they have again drilled more bore wells than open wells. The marginal positive groundwater balance in lean and average rainfall years could tilt to negative side very soon if the farmers continued drilling bore wells and pumping at the rate they have done from 1995 to 1999. Although the villagers acted collectively for water harvesting, there is no concern or awareness amongst the villagers for a sustainable use of groundwater. There is a need for community monitoring of groundwater and its allocation to individuals. There is an urgent need to bring in the change in the attitude of all the stakeholders where most solutions for water management are thought from increasing water availability and not from demand management. Increased rainwater and groundwater use efficiency could maintain the incomes as well as sustain development; however, the groundwater management will need community participation, social and institutional mechanisms along with the enabling policy mechanisms through suitable incentive as well as punitive measures with legal support and execution. This paper discusses the results from on-farm community watersheds through groundwater management as the drivers for sustainable management of watersheds dry land areas. The issues of sustainable development and management of the groundwater resource through integrated watershed management (IWM) approach are also dealt relative to food production and security.*

Introduction

Access to reliable groundwater sources plays an important role in food security in many cases as the access to reliable sources of water reduces the production risk. Farm incomes at both micro (farm) and aggregate (regional) levels are buffered from the effects of precipitation variability, drought or general water scarcity conditions. As a result, access to reliable groundwater supplies can ensure the income flow needed to purchase food; and it plays a key role in food production. As a result, there can be a direct link between water access and its efficient use and food security. While access to water is important in many situations, in others irrigated agriculture is only one of many income sources or available livelihood strategies. Consequently, fast decline in groundwater levels, irrigation system deterioration, droughts and other direct indicators of water scarcity can serve as signals that food security may be threatened. Water scarcity measures are warning signals, but they do not on their own indicate the emergence of food insecurity (FAO, 2002)

Yields in groundwater-irrigated areas are higher (often double) compared to those in the canal-irrigated areas (Shah, 1993; Meinzen-Dick 1996). In India, the groundwater-irrigated area accounts for about 50 per cent of the total irrigated area and up to 80 per cent of the country’s total agricultural production may, in one form or another, be dependent on groundwater (Dains and Pawar, 1987). However, the presence of groundwater irrigation alone cannot ensure increased yields as documented around the world. Groundwater availability needs to be seen as part of a complementary and mutually reinforcing set of other production technologies. Groundwater availability acts as a trigger to enable the farmers to invest in complementary inputs that, in combination, increase crop yields substantially. In the dry land SAT areas, an integrated watershed management resulted in increased groundwater availability that served as an entry point for increasing agricultural production and improving rural livelihoods (Wani et al. 2003, 2009).

Recent evaluations of the implications of water scarcity for food security range from the optimistic to the pessimistic. For example, Brown (1999) contends that primarily because of impending water shortages in northern China, the country will have to import up to 370 million tons of grain per year to feed its population in 2025. This massive increase in imports could cause steep increases in cereal prices and disruption of the world market (Seckler *et al.*, 1999). On the other hand, analyses by FAO and the International Food Policy Research Institute (IFPRI) indicate that yield increases (rather than increases in cultivated area) will be the dominant factor underlying the growth in cereal production in the coming decades and that, in aggregate, production increases will be sufficient to meet the demand (Rosegrant and Ringler, 1999; FAO, 2002a).

Food security is a function of three factors: availability; stability; and the ability of individuals to have access to food. As Sen (1999) and others (Dreze *et al.*, 1995) have argued that during famines in India, starvation is frequently due to the inability of individuals to purchase supplies that are readily available in the market and is not a function of food availability as such. Sen's approach may have particular relevance for analysing the impact of emerging groundwater problems on food security. Studies made in the late 1980s highlighted the critical role that access to water, particularly groundwater, plays in poverty alleviation (Chambers *et al.*, 1989). Reliable water supplies are a foundation that enables farmers to afford access to a wide range of development benefits (from food to education and health services) and can also enable farmers to diversify into other, often non-agricultural, income sources. These benefits are accessed through the improved yields enabled by the green revolution package of inputs. However, they carry a substantial risk because farmers must make investments in fertilizer, seed and other inputs in order to achieve them. These investments, which are often made through credit, will be lost if water supplies fail. Consequently, any decline in access to groundwater could have a major impact on the economic condition of small rural farmers.

The economic dimension is also central to understanding of the implications of groundwater over-extraction. Most discussions of groundwater over-abstraction emphasize the distinction between economic depletion (i.e. falling water levels make further extraction uneconomic) and the actual dewatering of an aquifer. Large-scale aquifers are depleted in an economic sense (the physical limits to pumping and associated energy costs) long before there is any real threat of physical depletion. Furthermore, wells owned by small farmers are generally shallow. In the context of poverty and famine, the falling groundwater tables will tend to exclude those farmers who cannot afford the cost of deepening wells long before they affect water availability for wealthy farmers and other affluent users (Moench, 1992). Consequently, substantial declines in water levels are particularly likely to have a major economic impact on farmers with limited land and other resources. This impact will tend to be particularly pronounced during the drought periods when a large numbers of small farmers could simultaneously lose access to groundwater as their wells dry up. A more creeping problem would occur during the non-drought periods as water-level declines undermined the economic position of small marginal farmers, forcing them onto already saturated unskilled agricultural and urban labour markets. The food security crisis in both these situations would be economic rather than related to food grain availability per se.

Groundwater, which is 38.5 % of the available water sources of the country, plays a major role in irrigation, rural and urban drinking water supply and industrial development. Groundwater meets nearly 55 % irrigation, 85 % of rural and 50 % of urban and industrial needs (Government of India, 2007). The use of groundwater in the agriculture sector has expanded rapidly because of the short gestation lags with which it can be developed, control over irrigation that it provides, free or subsidized availability of power in some states, water requirements for the crop production during critical growth stages caused due to erratic rainfall in dry land agriculture and paucity of surface irrigation.

The average annual rainfall in the country is 1170 mm, which correspond to an annual precipitation of 4000 billion cubic meters (BCM). Out of this volume of precipitation, 1869 BCM appears as average annual flow in rivers. Due to various constraints, only 1123 BCM is assessed as the average annual utilizable water (690 BCM from surface water and 433 BCM from groundwater). The present total water use is 643 BCM of which 83% is for irrigation. This is projected to grow to 813 BCM by 2010, 1093 BCM by 2025 and 1447 BCM 2050, against utilizable quantum of 1123 BCM. As regards to use, the extent of extraction has increased significantly over the years due to steep increase in the number of wells (tube and open wells). The average rate of increase in number of wells per year in India was 2.3%. The number of tube and open wells increased at the rate of 6.3% and 2.4% per year, respectively. It is estimated that currently there are 19 million wells in the country, out of which 16 million wells are in use and drawing about 213 BCM of water (Government of India, 2007).

According to the report on the 3rd Census of Minor Irrigation schemes (2005), the ultimate irrigation potential from groundwater source is 64.05 million ha, as compared to 46 million ha of land currently under groundwater irrigation. The report however, has revealed further scope for developing groundwater in some area (such as the eastern and north-eastern part of the country), but in many states, the irrigation potential created has exceeded the ultimate potential, showing that mining of groundwater, that is exploitation beyond the present level of dynamic resource (Table 1). The over-exploitation of groundwater in ten years (1995-2004) increased by more than 4.5 times, making groundwater use a matter of serious concern. The over-exploitation of groundwater in six states (Gujarat, Haryana, Punjab, Rajasthan and Tamil Nadu) is 54% against a national average of 28%.

Table 1. Groundwater exploitation status in India (1995 and 2004).

Total number of assessment units (Blocks/Mandals/Taluks/Watersheds)	Year	Over-exploited	
		(No.)	(%)
7063	1995	428	6
5723	2004	1615	28
(Source: Ministry of Water Resources, 2005)			

The prime cause of over-exploitation of groundwater is the rising demand from agriculture and rapid growth in urbanization and industrialization. In many groundwater irrigated areas, the decisions on cropping pattern and cropping intensity are being taken largely independent of the groundwater availability. Thus water intensive crops have tended to be grown in the face of scarcity of water. Such distortions occur partly due to the legal/regulatory regime governing groundwater (Aithal, 2007). In many states, groundwater extraction has exceeded annual recharge and water tables have gone down (Batchelor et al. 2000). Since groundwater is an open access resource, tragedy of commons occurs where everyone tries to extract as much as possible, leading to sharp degradation of the resource. There is an obvious urgency about managing groundwater in a sustainable way, which is an important driver for the sustainable development and management of productivity in dry land areas (Wani et al. 2005).

Over-exploitation of groundwater leads to: reduction in water yield in the wells, increase in pumping depth and cost of pumping, contamination of groundwater due to geogenic factors, resulting in increasing levels of fluoride, arsenic, iron and most importantly, in the failure of wells causing heavy economic losses to the farmers. The groundwater management rather than development is the major challenge facing the water resources, particularly in the dry land areas. Therefore, a focus on the development activities must be balanced by integrated management mechanism to achieve a sustainable utilization of groundwater resources, which is an important driver for the management of watersheds for sustainable development in the dry land areas.

Sustainable Groundwater Development and Management through IWM Approach

Groundwater is an invisible and endangered open or common access resource. Overexploitation of the groundwater beyond the sustainability limits in several parts of the country has resulted in widespread and progressive depletion of its levels in selected pockets of 370 (61%) out of 603 districts in the country (MOWR, 2005). In 15% of the blocks, the annual extraction of groundwater exceeds the annual recharge and in 4% of the blocks it is more than 90% of the recharge (CGWB, 2006). Reduction in groundwater supply, saline water encroachment, drying up of the springs and shallow aquifers, increased the cost of pumping by replacing centrifugal pumps with expensive submersible pumps, reduction in free flow, weakening drought protection and even local land subsidence in some places are threatening the sustainability of the aquifers. In many areas this has occurred more or less year-on-year, except for a temporary respite following years of exceptional monsoon rainfall when a partial recovery has been observed. The practice of the sale of water, either in cash or on crop sharing basis has also encouraged the rich farmers to construct deep tube-wells and over pumping the groundwater. Rapid decline in groundwater levels in the drier parts of India's a matter of concern, since demand-driven exploitation without regulatory measures and understanding of the area-specific problems lead to crisis not only for the present but may also result in damage to the groundwater system with adverse impact on the future water supply. It has been reported that the declining groundwater levels could reduce India's harvest by 25% or more (Singh and Singh, 2002). The other important part of the decline in the utility is related to the groundwater quality. The leachates from the compost pits, animal refuse, dumping grounds for garbage, synthetic fertilizers and pesticides enriched irrigation return flows, seepage from septic tanks, seepage of sewage have adversely affected the groundwater quality in several parts of India. Geogenic contaminants such as unsafe concentration of arsenic, fluoride and iron are related to excessive groundwater pumping. The depletion and degradation of groundwater is a major cause for increasing the rural poverty in India. Groundwater management deals with a complex

Figure 1. Runoff harvesting structures constructed in community watersheds in India.

interaction between human society and physical environment and presents a difficult problem of policy design. Aquifers are exploited by human decisions and overexploitation cannot always be defined in technical terms, but as a failure to design and implement adequate institutional arrangements to manage people who exploit the groundwater resource (Sharma, 2009).

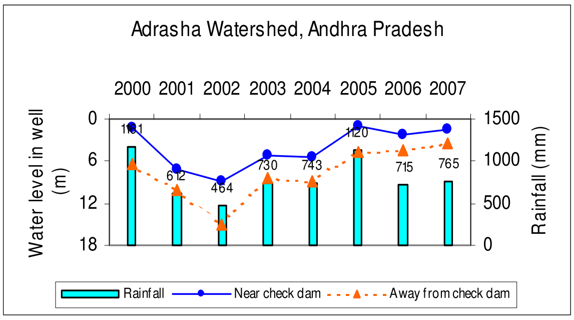
Rainwater is the main source of water for agriculture but its current use efficiency for crop production ranges only between 30 – 45 %. Integrated Watershed Management (IWM) is the strategy adopted to enhance the water use efficiency for sustainable development of dry land areas. The IWM strategy demonstrated that dry land areas with good quality soils could support double cropping, while the surplus rainwater could recharge the groundwater. In IWM, the emphasis is on *in-situ* conservation of rainwater at the farm level with excess water taken out from the fields safely through community drainage channels and stored in suitable low-cost water harvesting structures (WHS). The stored water is used as surface irrigation or for recharging the groundwater. Main components of IWM in addition to rainwater conservation and harvesting include use of appropriate crops, improved crop varieties, cropping systems, and nutrient and pest management for increased productivity and water use efficiency (Wani et al. 2005).

Long-term on-station research at ICRISAT demonstrated that the Vertisols with a rainfall of 800 mm y^{-1} have the capacity to feed 21 persons per ha (producing food grains 5.1 t ha^{-1}) compared with current productivity of 1.1 t ha^{-1} supporting 4-6 persons per ha y^{-1}. This increased productivity is achieved with two fold increase in rainwater use efficiency from 30 % to 67 %, reduced soil loss by 75 %, and reduced runoff loss by 66% as compared to the traditional system of cultivation (Wani et al. 2003).

At the landscape level, community watershed management is used as a growth engine for sustainable development in dry land regions of Asia through management of rainwater efficiently for enhanced crop productivity on a sustainable basis through an innovative participatory IWM approach involving consortium and the convergence of several institutions, were implemented (Wani et al. 2003, 2007 and 2008a). This The participatory research and development approach at benchmark sites in several states/provinces in India, Thailand, Vietnam and China, representing different semi arid tropical agroecoregions has improved productivity (up to 250 %) and groundwater levels, while minimizing the degradation of the natural resources. The consortium strategy brings together institutions from the scientific, non-government, government and farmers group for knowledge management. Convergence allows integration and negotiation of ideas among actors. Cooperation enjoins all stakeholders to harness the power of collective action. Capacity building engages in empowerment of the communities for sustainability (Wani et al. 2005 and 2006). This approach has vastly improved the livelihoods of 50,000 poor people in 368 watersheds across Asia.

Figure 2. A recharged open well with pump for irrigation at Shekta watershed, Maharashtra.

Improving the availability of water (surface and groundwater) attributed to efficient management of rainwater and *in-situ* conservation (watershed-based efficient land management system, viz. contour cultivation, conservation furrows, broadbed and furrow system etc.) and establishing water harvesting and recharging structures especially low-cost structures (viz. percolation tanks, sunken pits, check dams, gabions and gully plugs etc.) through out the toposequence improved groundwater levels benefiting more number of small farmers (Fig. 1 and 2). *In-situ* water conservation measures were greatly helpful in reducing the pressure on groundwater extraction for crops by improving moisture regime in soils.



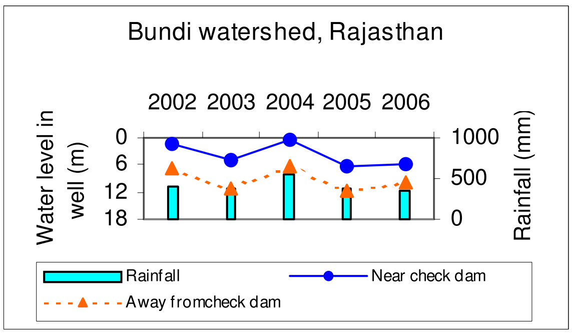


Figure 3. Mean annual groundwater levels in wells as influenced by the WHS at Kothapally and Bundi watersheds, India

In the various watersheds in India such as Adarsha watershed in Kothapally, Andhra Pradesh, Bundi watershed in Rajasthan, and Laltora, Dewas and Madhusudhangadh watersheds in Madhya Pradesh, even after rainy season, the water levels in wells nearer to WHS sustained good groundwater yield (increase in quantity and duration) compared to those wells away from WHS (Fig. 3). In the Lalatora watershed in Madhya Pradesh, the groundwater level in treated area registered an average rise of 7.3 m, at Bundi watershed in Rajasthan 5.7 m increase was observed and at the Adarsha watershed, Kothapally in Andhra Pradesh 4.2 m rise in groundwater was recorded (Wani et al., 2003). The total recharge taking place through natural and water harvesting interventions is greatly affected by the amount of rainfall, its intensity, duration of the monsoon, ground and sub-surface characteristic (i.e. percolation rate and runoff coefficient). The various WHS resulted in the average contribution of seasonal rainfall during normal rainfall year to groundwater ranged from 27 to 34 per cent. (e.g. Adarsha watershed, Kothapally, AP was 27 %, Lalatora watershed was 29 % and Rajsamadhiayala watershed, Gujarat was 34 %) (Pathak et al. 2002 and Sreedevi et al. 2006).

A detailed study of groundwater scenario in the Rajsamadhiayala watershed, Gujarat during pre- and post-watershed interventions revealed that the mean total groundwater recharge has increased by three folds in different rainfall situations and the water requirement has doubled after the watershed interventions due to increased cropped area, cropping intensity and change in the cropping pattern (Table 2) (Sreedevi et al. 2006). There existed as many as 255 open wells existed in 1995 with very less yield with an average water column of 5.9 m, but after 10 years (2004), there were 308 wells with mean water column of 10.4 m (Fig.4). The increase in water column during the *kharif* was 6.6 m, 5.3 m in the rabi, and 1.3 m in the summer. Overall, there was an increase of 4.4 m of water column in 2004 compared to that of 1995. This had a direct impact on the agricultural production and income, which have increased considerably. But productivity data suggests that there is still a good scope to increase the productivity per unit of water used by implementing appropriate water use efficiency measures.

Table 2. Pre- and Post-interventions scenario of total water requirement for crop irrigation and total groundwater recharge for good, average and lean rainfall years in Rajasamadhiyala watershed, Gujarat.

Rainfall year	Pre-intervention groundwater (GW) scenario (in MCM)			Post-intervention groundwater (GW) scenario (in MCM)		
	Total GW recharge	Total water requirement for irrigation	Net ground water balance	Total GW recharge	Total water requirement for irrigation	Net ground water balance
Good	1.40	1.08	0.32	4.03	2.31	1.69
Average	1.00	0.86	0.14	3.13	1.8	1.33
Lean	0.41	0.42	-0.01	1.07	0.95	0.12

Not only increase in the water column is observed, significant improvement in the water yield in wells were also reported as was evident by the duration of pumping hours per day for irrigation. The average pumping duration of 5.25 h per day in 1995 increased to 10.4 h per day in 2004, which means that there is a net increase of 5.2 h per day of pumping duration (Sreedevi et al, 2006).

Similarly in the Bundi watershed, Rajasthan, soil water conservation and rainwater harvesting interventions resulted in significant improvement in groundwater both in terms of duration of water available and the water yield from the wells. Before the watershed interventions, only 88 wells use to have water for 8 to 12 months in a year, whereas after the watershed interventions it increased to 187 wells (Fig. 5). Before watershed interventions, 52 wells out of 227 were functional only for 1-4 months mainly during the rainy season, where as after the watershed interventions particularly due to the construction of WHS, majority of the seasonally functional wells have become functional through out the year. Similarly, the mean depth of water column in the wells before the watershed interventions was 4.5 m, compared to 9.5 m after the interventions (Fig. 6).

There is a substantial increase (more than 100%) in the mean depth of water column in the wells after the watershed interventions. Particularly during the post-rainy season, the depth of water column in the wells has increased substantially. There is a three-fold increase in the mean pumping duration, substantial improvement in the water recovery or recharge period and area irrigated by wells during post watershed interventions periods (Table 3).

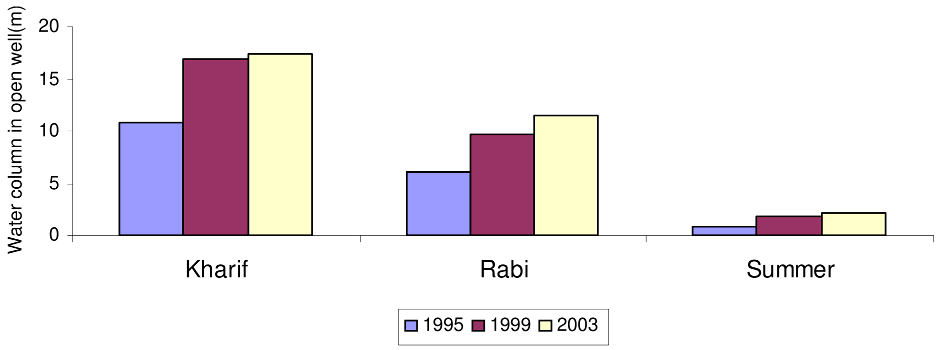


Figure 4. Average water column in open wells in Rajasamadhiyala Watershed, Gujarat,

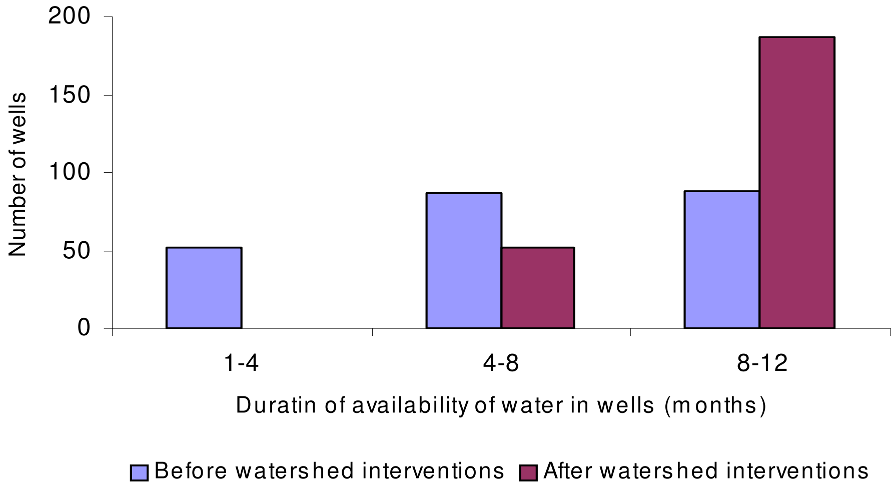


Figure 5. Effect of watershed intervention on duration of groundwater in Bundi watershed, Rajasthan (Source: Pathak et al. 2007)

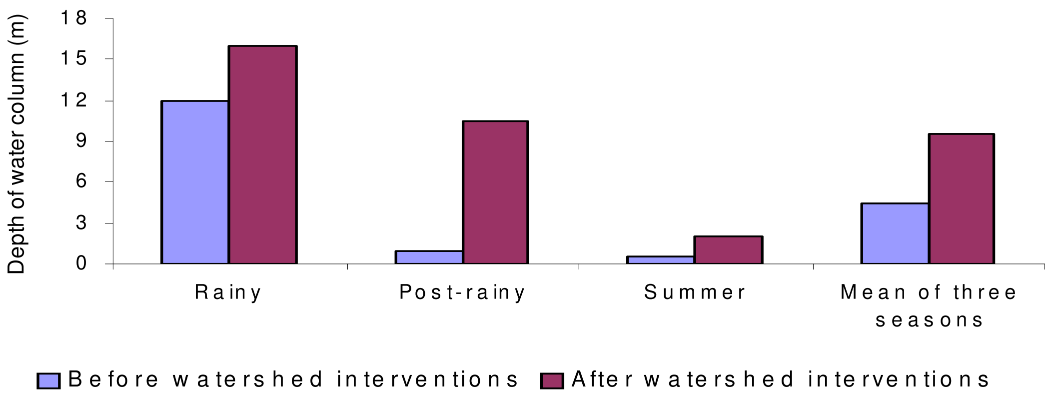


Figure 6. Effect of watershed intervention on water column in open wells, Bundi watershed, Rajasthan (Source: Pathak et al. 2007).

Table 3. Number of total and active wells during the year in watershed before and after rainwater harvesting interventions

	Before Watershed Development				After Watershed Development			
	Total No. of wells	1-4	4-8	8-12	Total No. of wells	1-4	4-8	8-12
Rajasamadhiyala, Gujarat	255	120	77	18	308	12	88	208
Goverdhanpur-Gokulpur, Rajasthan	227	52	87	88	239	-	52	187
Shekta, Maharashtra	189 (133 functioning)	73	35	25	280 (271 functioning)	110	113	48

Overall, there is an increase of 48 % in the total number of wells and 51 % increase in the seasonally functional wells (1-4 months), while there is a drastic increase of 223 % wells functioning during 4-8 months in a year and 128 % increase was observed in perennially functioning wells (8-12 months in year). An average water column of wells through out the year was 1.02 m before the watershed intervention, whereas after the watershed interventions were implemented the water column in wells was 3.17 m, which shows an increase of about 211 % in the water column.

Impact of Groundwater Management on Crop Production and Food Security

In the Rajsamadhiayala watershed, Gujarat, the increased availability of water in the wells increased the area under irrigation significantly, particularly in the summer (Table 4). In the case of the Bundi watershed in Rajasthan, the area under irrigation increased by 66% after the implementation of the watershed program. Area under rainfed agriculture reduced due to increased availability of water in the watershed. This resulted in marked reduction in crop failures in the watershed area and increased farmers 'confidence to invest in improved agricultural inputs. In addition, about 35 ha land was brought under horticulture with irrigation facility (Table 5).

Table 4. Area under irrigation (ha), 1995-2003, Rajsamadhiayala watershed, Gujarat

Cropping season	1995	1999	2003	% Increase in 2003 over 1995
Kharif	402	518	643	60
Rabi	356	469	551	55
Summer	11	18	24	118
Total	769	1005	1218	58

Table 5. The changes in land use pattern at Gokulpura-Goverdhanpura watershed, Bundi during 1997-2004.

Land use system	Area (ha)	
	Before watershed interventions (1997)	After watershed interventions (2004)
Irrigated	207 (15)*	343 (25)
Rainfed	327 (24)	209 (15)
Pasture	167 (12)	114 (8)
Horticulture	Nil	35 (3)
Forest	360 (27)	360 (27)
Dwelling and river	294 (22)	294 (22)
Total	1355	1355

* Values in parentheses are the percent of total area; Source: Pathak et al. 2007

The changing scenario in the land use pattern due to watershed development in the Shekta watershed clearly revealed a significant increase in the irrigated area (96 % for seasonally irrigated 88 % in perennial irrigated). There is also an increase in the area of pasture/grazing land. All cultivable fallow area was totally brought under cultivation (Table 6).

Table 6. Land Use Pattern in the Shekta watershed, Maharashtra.

	Area under different land use (ha)	
	Before watershed interventions (1998-99)	After watershed interventions (2004-05)
Rainfed	675.60	581.34
Seasonally Irrigated	94.51	185.24
Fully Irrigated	64.28	120.52
Pasture/ grazing	00.00	32.68
Cultivable wasteland	85.39	00.00
Govt. forest	132.60	132.60
Total	1052.38	1052.38
Source: Sreedevi et al.2008		

Increased Farmers' Investment with Water Availability

The increased availability of water in wells encouraged farmers to invest more to acquire improved irrigation facilities. With increased groundwater availability, the private investments in farming increased (Table 7-9). The number of diesel engine pumps declined by 22 % over the period (1995 to 2003), while there was considerable increase by about 80 % in the electric motor pump sets in the Rajasamadhiyala Watershed. Farmers increased investments in irrigation equipments as was evident from 156 % growth in the number of farmers with the equipments, which helps in preventing the water loss through seepage and increases the irrigation efficiency (Table 7). There was a considerable increase in procurement of drip and sprinkler irrigation sets also.

Table 7. Change in irrigation facility and equipments available in watershed (1995-2003), Rajasamadhiyala Watershed, Gujarat, India.

Irrigation facility/equipments	**1995**	**1999**	**2003**	**Increase or decrease (%)**
Diesel engine pumps	208	188	162	-22
Electric pump	205	281	368	80
No. of farmers procured pipeline	48	84	123	156
Drip irrigation set	16	22	38	138
Sprinkler irrigation set	1	2	4	300

Due to the increased availability of groundwater, total number of farmers having access to irrigation increased by 188 % from 1995 to 2003. There is a sharp increase in the number of small and marginal farmers who have access to irrigation compared to large farmers (172 %) increased by 292 and 317 percent, respectively (Table 8) (Sreedevi et al. 2006).

Table 8. Change in the number of farmers having access to irrigation, Rajsamadhiayala watershed, Gujarat.

Farmers category	**1995**	**1999**	**2003**	**Increase in 2003 over 1995 (%)**
Small	25	82	98	292
Marginal	16	28	35	317
Large	32	65	87	172
Total	73	175	210	188

Post-project scenario revealed about 76% increase in the number of diesel pump sets and 38% increase in the electric pump sets for lifting irrigation water along with the increase in the pipeline to save water from seepage loss (Table 9) in the Gokulpura Watershed in Rajasthan (Pathak et al. 2007)

Table 9. Effect of Watershed programme on irrigation equipments at the Gokulpura-Goverddhanpura watershed.

Irrigation Equipment*	Before watershed interventions		After Watershed interventions	
	No. of equipments	No. of families	No. of equipments	No. of families
Chadas(Traditional method)	164	221	110	151
Diesel pumps	79	145	139	202
Electric pumps	8	18	11	18
Pipe line length(m)	1685	50	5982	82

*Some of the equipments jointly owned by the families; Source: Pathak etal 2007

Increased Crop Productivity and Food Security

Increase in crop productivity is common in all watersheds due to watershed interventions in a short span of time. In the Adarsha watershed, Kothapally, Andhra Pradesh, integrated watershed management technologies increased maize yield by 2.5 times and sorghum yield by 3 times. Overall, in the 65 community watersheds, implementing best-bet practices resulted in significant yield advantages in sorghum (35-270 %), maize (30-174 %), pearl millet (72-242 %), groundnut (28-179 %), sole pigeon pea (97-204 %), and intercropped pigeonpea (40-110 %). The results in Figure 7 show a similar trend in the Bundi watershed, Rajasthan. In the Adarsha watershed, Kothapally, Andhra Pradesh, (Wani et al. 2006, 2009) due to additional groundwater recharge, a total of 200 ha were irrigated in the post-*kharif* season and 100 ha in post-*rabi* season, mostly to vegetables and flowers.

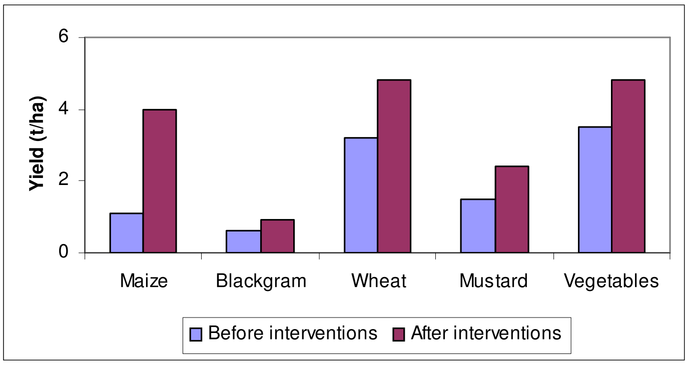


Figure 7. Crop productivity before and after interventions at Bundi watershed, Rajasthan.

Integrated watershed management through primarily water (surface and groundwater) conservation and management compounded with other improved practices have shown a significant increase in productivity, cropping intensity and income, while controlling degradation of natural resources (Table 10). Compound growth rate (CGR) of productivity, net returns and benefit cost (B:C) ratio are mean of selected major crops. In the case of Kothapally watershed, the increase in cropping intensity, B:C ratio and per capita income ranged 30-55 %, 45-88% and 19-78 % respectively in community watershed after the implementation of watershed interventions over the baseline data.

Table 10. Growth rate of productivity, net return, increase in cropping intensity, B:C ratio and per capita income due watershed interventions from community watersheds in India.

Watershed	Compound growth rate		Increase in Cropping intensity (%)	Increase in B:C ratio (%)	Increase in per capita income per year(%)
	Productivity	Net returns			
Kothapally, Andhra Pradesh* (1999-2006)	101%	34%	30	88	78
Bundi, Rajasthan (1997-2004)	6.5 - 14.3	7.9 - 36.3	55	45	28
Rajsamadhiayala, Gujarat (1995-2003)	4.6 - 9.1	8.7 - 21.6	44	55	39
Shekta, Maharashtra (1999-2005)	2.2 - 16.6	4.5 - 22.7	30	47	19

** productivity and net returns are the percent increase after intervention over the base line data*

Food Security is a state of assuring the physical availability and economic accessibility to enough food (in an environmentally and socially sustainable manner) in terms of quantity (safe, nutritious, balanced), quality (amount, distribution, calories) and cultural acceptability for all people at all times for a healthy and active life.

The various measures implemented through the integrated watershed management program, particularly improving the sustainability of groundwater source, have improved the food, fodder and fuel security over a period of time (Fig. 17). The results in Table 11 reveal the availability and requirement of food per capita per month in monitory value to measure the food gap as well as security in the Rajasamadhiayala watershed in Gujarat. In 1995, per capita food secured was only 20 percent against requirement, while the food security increased drastically by 71 % in 1999, where as in 2003-04, the total per capita food security was attained (109 %) owing to the overall development activities of the watershed programs in general, particularly due to additional water availability through rainwater harvesting and groundwater recharging structures (Sreedevi et al. 2006).

Table 11. Food security over period of Time in Rajasamadhiyala Watershed

	Unit	**1995**	**1999**	**2003**
Total Population	No	1631	1691	1747
Land Availability per capita	ha	0.446	0.442	0.437
Land value	Rs. 100000	0.558	1.336	1.747
Income from all sources				
Interest on land	Rs. 100000	0.0335	0.0802	0.1048
Crops	Rs. 100000	18.75	169.69	306.57
Animal husbandry	Rs. 100000	11.41	11.26	11.6
Other Income (services/employment)		0.78	1.02	1.45
Total Income		30.97	182.05	319.72
Income per capita	Rs.100000 per month	0.019	0.108	0.183
Income Availability	Rs. per month	437.05	1564.91	2398.11
Income Requirement	Rs. per month	2200.00	2200.00	2200.00
Food Gap Rs. (Required-Availability)*		-1762.95	-635.10	198.11
Food security per capita per month (%)		19.866	71.132	109.005
* Rs 2200 per capita per month are calculated based on the defined of World Food Summit, 1996, Rome, to measure food security (availability, acceptability and utilization).				

In the case of fodder security, only 61 per cent was secured in 1995, while in 1999, it was fully secured (103 %) within a short span of time (Table 12). The fuel security also improved in 1999 (138 %) compared to 1995 (Table 13).

The science-led participatory watershed development and management through consortium and convergence approach enhanced the agricultural productivity, food security and incomes, decreased poverty of rural poor, reduced labor migration and improved environmental quality.

Table 12. Fodder security over period of time in Rajasamadhiyala.

	Unit	1995	1999	2003
Total animal	No	1743	1526	1235
Total area	Ha	1075	1075	1075
Area under fodder	Ha	404	381	501
Area under fodder (%)		37.58	35.44	46.60
Fodder productivity	kg ha^{-1}	5739	7979	7590.5
Fodder production	kg $year^{-1}$	2318556	3039999	3802840.5
Fodder from by-product	kg $year^{-1}$	1456805	1967169	2296282.5
Total fodder availability kg $year^{-1}$		3775361	5007168	6099123
Fodder requirement	kg $year^{-1}$	6175251	4879453	5597122
Fodder insecurity	kg $year^{-1}$	-2399890	127715	502001
Fodder insecurity	kg $year^{-1}$ $animal^{-1}$	-1376.87	83.69	406.48
Fodder security per animal per annum (%)		61.14	102.62	108.97

Table 13.Temporal change in fuel security in Rajasamadhiyala.

	Unit	1995	1999	2003
Total Population	No	1631	1691	1747
Total Area	Ha	1075	1075	1075
Area under fuel	Ha	335	411	395
Area under fuel (%)		31.16	38.23	36.74
Production of cotton residue for fuel	kg $year^{-1}$	565251	720722	697453
Production of others fuel	kg $year^{-1}$	14822	15382	16123
Total Production	kg $year^{-1}$	580073	736104	713576
Fuel requirement	kg $year^{-1}$	473043	534364	627432
Fuel requirement	kg $year^{-1}$ $person^{-1}$	290.03	316.00	359.15
Insecurity of fuel	kg $year^{-1}$	107030	201740	86144
Fuel security per capita/ year (%)		122.63	137.75	113.73

Conclusions

Groundwater development in the country has expanded extensively. Over-exploitation of the resource in most parts of the country has led to a rapid decline in the groundwater table. This has threatened not only the food security and environment, but also the sustainable development. Further depletion of groundwater resource has been affecting the small and marginal farmers the most, threatening their livelihood in many cases. The sustainability of groundwater use is one of the core areas, which requires major attention for meeting the water requirement and ensuring food security. An important way of addressing the issue is by augmenting the groundwater supplies in the shallow aquifers on micro watershed basis through groundwater recharging and rainwater harvesting system. Our experience from community watersheds showed that recharging can be made much more effective by the use of scientific inputs and analysis than otherwise. It may however be noted that even if the entire potential of recharge is utilized, shortage will still persist, underscoring the need of improving water use efficiency and limiting extraction of groundwater. In limiting the extraction, probably the legal regime alone would not meet the goal but participatory management of water resources ensuring equity along with enabling policies to incentives promotion of water efficient technologies and crops along with punitive measures are needed. While the measures suggested in the National Water Policy to promote sustainability of groundwater should be the cornerstone in the groundwater development and regulation strategy in the country (Government of India, 2007).

Sustainable groundwater development and management in the overexploited regions needs to be taken up by incorporating artificial recharge to groundwater from in-situ and ex-situ rainwater harvesting through integrated watershed interventions, management of salinity ingress in coastal aquifers, conjunctive use of surface- and groundwater, management of poor/marginal quality groundwater, water conservation by increasing water-use efficiency, regulation of groundwater development and extraction, etc. Several studies conducted in the community watersheds through integrated watershed management approach have concluded that these technologies have been successful in the sustainable development; and the management of groundwater resource would be the key to achieve breakthrough in agricultural production and food security.

Access to groundwater can be a major engine for food security, poverty alleviation and economic development in the rural areas. The effective management and utilization of groundwater not only as a source of water for agriculture and other consumptive purposes, but also as a supplementary source of surface water flows, wetlands and wildlife habitats calls for an increased attention to the two major and interdependent source of concern: depletion and pollution. Therefore, the focus on the development activities must be balanced by management mechanisms, enabling policy and institutional mechanisms to achieve a sustainable utilization of groundwater resources. The groundwater management rather than development is the major challenge facing the organizations/institutions dealing with water resources.

Acknowledgement

We sincerely acknowledge the help of farmers and partner NGOs from different watersheds studied for their help in collecting data. We also gratefully acknowledge financial support from the Asian Development Bank, Manila, Philippines, Sir Dorabji Tata Trust, Mumbai and Government of Andhra Pradesh for Community Watershed Programs.

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Community Driven Approach for Artificial Recharge –TBS Experience

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Abstract

In India, small water reservoirs in the desert area are a part of a complex inter-linking natural resource management system. Traditional methods of water harvesting were employed by the local communities led by TBS to rejuvenate a local river, recharge the ground water and re-green a village. In Alwar district, 8600 small water harvesting talabs in 1086 villages have been built since 1985. This has resulted in rise of water level in the shallow aquifer, increase of area under single and double crop, and increase in forest cover through social forestry and agro forestry. The villagers have also formed an 'Arvari Sansad' to frame rules of water use. The efforts towards water conservation have numerous positive impacts on the communities inhabiting the area. Employment opportunities have increased and migration has reduced substantially. The paper outlines the community driven approach for artificial recharge using traditional techniques of water harvesting. The paper emphasizes that mobilization of civil society and the community for action on natural resource management and conservation for rural uplift in India is the way to save the environment and bring prosperity to farmers in Indian villages.

Introduction

This is a saga of complete ecological change through community action in the desert and semi desert regions of Rajasthan, brought about by water harvesting.Back in 1985 four young men resolved to take up the challenge of stalling the ecological disaster of desertification. However, before I talk about this, let me tell what was happening prior to the community action on water harvesting invoked in 1985, to see the impact of changes on the ecological front today. Also let me relate clearly the role of water in climate change.

Environmental scene in Rajasthan in 1985

In the semi arid region of Rajasthan, especially in Alwar district, excessive drawing of ground water for crop production resulted in its shallow water table aquifers dwindling to very low levels, as low as 100 to 120 meters. Deep confined aquifers, some times as deep as 300 meters, are either salty or too deep to pump. This left only about 11 per cent of the lands under single cropping out of which only three per cent of the land of Alwar district remained under double cropping. The forest cover in the area, which includes the famous Sariska Tiger Reserve, got reduced to about seven per cent-that is about 6,500 square km. The people were deserting their villages to earn a meagre living elsewhere as very little farming was possible, precious little was left as pasture lands for grazing the cattle and no new tree growth or forest regeneration was taking place. Thus the farmers of this region could grow neither much food, nor fodder or pasture, nor any fuel wood for their rural energy needs. It was a harsh desert climate becoming unbearable due to complete exhaustion of ground water. When rains came (average about 16-50 cm/year), they came in 3-4 high intensity events in 7-10 days rainy season, resulting into its loss as run off, leaving behind thirsty lands.

Water harvesting for carbon fixation and sequestration to reverse climate change

In the absence of water there is very little growth. When there is no vegetation, there is no carbon fixation in to the soil and no carbon sequestration. Thus the temperature increases. I am aware that various models of climate change predict an increase in temperatures of 2-4 degree C in coming 100 years and a disaster is predicted. However, with correct community efforts, if encouraged by all, especially if facilitated by governments in power, it can be reversed.

The carbon build up in the atmosphere is to be arrested on all fronts where carbon is pumped into the atmosphere. However, it is only vegetation (crops, pastures, trees and forests), which sequesters it, and turns it into oxygen, which makes the atmosphere livable. Organic agriculture fixes crop residue by its incorporation into the soil or by recycling the organic residue as composts, taking carbon out of the atmosphere. However, for vegetation to flourish, it needs water. Below are stories of community efforts in water harvesting carried out to stop environmental degradation and climate change.

An old village lady provides vision and becomes my water harvesting Guru

The four youths, including myself who went to live in the village of Mangu Meena and Mrs. Nathi Bhalai[2] in 1985 for rural uplift, were inspired by Gandhian model of rural development. Our idea was to bring prosperity to this semi-arid village but soon we were very depressed seeing no solution around. Two among us left thinking nothing could be done. However, even though I was depressed, I was not willing to give up. In this mood of desperation, Mangu Meena advised me to build talabs (small water dams to stop, store and recharge the ground water). Nathi Bhalai (a lower caste destitute) consoled me by saying, 'you fool you have not understood what is needed'. You need to build talabs so that the water does not run off but is held back to percolate to the ground. With Nathi Bhalai -- whom I call my guru, who showed me the direction-on my side I decided to dig for building a dyke in the village to create a talab. Seeing two of us digging dykes, some of the village youth laughed while others started joining us in digging and making the dyke. Rest is history now. Once the first small talab was ready, the villages saw water. In the surroundings the ecology changed in the very next season. This became an example of how to start restoring the ecology for better food production, vegetation rejuvenation and river restoration.The idea spread like fire in the parched villages. Village people started approaching me for helping them to do the same in their areas.

India has a tradition of water harvesting (Mishra, 1994, 1995) which in modern times seems to have been lost. Hence let us look at some of the traditional water harvesting systems in India as reported by Miss Sheena (1997).Carrying a spade and basket and accompanied by Nathi Bhalai of Gopalpura village, we started building a dyke to hold water in the hot sun in village Gopalpura. That was 23 years back, in November 1985. By now the community has built over 8,600 such talabs in over 1,068 villages in the district of Alwar alone over an area of 6,500 square km under the leadership of Tarun Bharat Sangh (TBS literal translation, "Indian Youth Association"). There are many such efforts going on in India. I shall recount some of them below (Sheena, 1997).

Revival of ecology by *talaabs*, *johads* and *chaals* in India

Traditional methods of water harvesting flourishing today through the efforts of noble Gandhian souls Anupam Mishra[3] (1995), who is recognized as an authority on traditional water harvesting systems in India, rightly says "hundreds and thousands of traditional, small reservoirs (tanks) did not appear all of a sudden from the blue in India in older times. For each promoter of tanks, there were tens of people who actually worked on these tanks. These 'ones' and 'tens' combined to make hundreds and thousands. But a society brought up on superficial modern education that it has acquired in the past 200 years - has reduced these tens, hundreds and thousands into non-entities.

The stethoscope of modern thinking has pronounced many traditional rural cultures and self-sufficient societies as backward, obsolete and incapable of sustaining themselves without comprehending or admitting to the causes of disruption and destabilization of the independent self-sustaining rural societies. Yet, in many parts of the world examples of sustainable management systems can be found. In India, small water reservoirs in the desert areas were part of a complex inter-linking natural resource management system. It is based on this knowledge that all the civil societies movements for water harvesting in India are being built up.There are examples aplenty.

Johads in Alwar

In the district of Alwar, the Tarun Bharat Sangh (TBS, a youth civil society organization), led by myself, is today regarded with reverence, pride and sometimes awe by many living in villages close to the Sariska sanctuary in Rajasthan. Referred to as the "Ashram (spiritual house)" by the local people, it has become synonymous with the johads (talabs or small reservoirs) that today ripple with waves on the once eroded landscape of the Aravalli hills. Today at least 1,068 villages have altogether more than 8,600 small and big johads, built with the active and increasing local participation in an area of 6,500 square km. In the Aravalli hills most johads are built along contours of the mountain slopes for arresting and storing rainwater. During a heavy monsoon downpour in 1988, the people's johads stood firm while the government built dam at Jaitpura, costing more than one hundred thousand rupees, got washed away (Sheena, 1997).

i. Bhaonta - An Alwar village empowered, recharged and re greened

The Babajiwala Johad (johad is an earthen check-dam), the 160-meter long structure, has an earthen embankment with a masonry spillway and was built by the community. The embankment is 13 meter wide at the base and 1.3 meter wide at the top. It is 4.5 meter high and has a catchment area of 10.25 sq. km. The details that have gone into the making and maintenance of the dam are etched on a stone wall, 1.3-1.6 meters in height, that is meant to keep cattle from getting on to the embankment.

In its valley below, Sankhara ka Bandh, which owes its name to the site of construction that is enclosed in a narrow passage between the steep slopes of the adjoining hillsides-sankhara means narrow-- was renovated by the community. The cemented, stone-limed embankment has been built to withstand the great force and swift flow of water. With a catchment of 9 sq. km., the crescent-shaped, convex embankment has been raised across a length of 260 meters and is 7 meters high. Its base is a strong 7-meter wide, narrowing to 2.6 meters at the top.

These small dams have not only recharged all the wells in the village downstream but also contributed to the revival of the river Arvari, one of the main sources of which originates in Bhanonta-Koylala. The forest in the catchment of the johad does not look very green due to the nature of the ecology of the region: semi-arid, but it shows its colour during the rain. On the embankment of the Sankhra ka Bandh, a sign is painted that says "Bhairondev People's Wildlife Sanctuary", a mark of the respect the village has towards the wildlife that is an inherent part of the forest ecosystem. The village elders have put numerous self-imposed restraints, which are fully practiced by the village in obtaining forest produce. These have regenerated the forest in the valley.

The village leaders decided to select this site to build these small dams for following reasons:

1. The point was the narrowest in the valley;
2. The rock formation at that particular site was such that the dam just merged into it;
3. The site ensured that the embankment did not bear the brunt of the high-speed run- off; and
4. From past experiences, they knew that groundwater recharge would be the maximum at that site.

ii. A river revived – How farmers revive rivers and turn the sand dunes back

The beauty of the regeneration efforts facilitated by the Tarun Bharat Sangh (TBS) in the villages of Alwar (all above cases) is that the fruits of toil may not seem very obvious, but are definitely there. More to the point, they are long-standing and their impact is more visible downstream, as in the case of the river Arvari. Nowhere more so than at Hamirpur, a village downstream of Bhaonta-Kolyala, where the statue of River Arvari blesses all at the entry point itself. The perennial flow in the river is the result of the 95 johads and dams, such as the Babajiwala Johad and Sankhra ka Bandh, built by villagers upstream.

The village elders can tell you that this river was a mere barsati nullah (a monsoon drain or seasonal rivulet) that used to flow for less than a week during the rainy season. As a direct result of harvesting the run-off upstream, the river became perennial in 1996, and has not ceased to flow since then. Even in the hottest months of summer, there is plenty of water in the river. This is attributed to the 'base flow', cased by the upstream small dams built by the farmers, making the river perennial.

In fact the government had issued fishing license to contractors from outside the region soon after fish appeared in the river. When the residents of Hamirpur protested, the contractors put in Aldrin in the river to kill the fish. But the community did not give up the fight against the abuse of a river that belonged to them. After initial indifference on the part of the police, it appreciated the gravity of the situation and assisted the village in preventing any further unfortunate incidents. Despite new surface water resources, no incidence of malaria is reported, thanks to the fishes.

On way to Bhaonta from Thana Gazi, a narrow road divides the landscape ahead into two. The botched up efforts of government agencies can be seen alongside the success story of people's efforts based on traditional water harvesting models. The systematic process of conservation beginning with recharging of groundwater by percolation tanks, protecting the scant vegetation and allowing it to regenerate shows people's very own model of development. On the contrary, a top-heavy approach of building boulder check-dams along eroded mountain slopes and contour bunding by government departments has only escalated soil erosion and gullies.

iii. Extracting prosperity from sand - Nimbi's Green revolution.

In contrast to Alwar villages, this area in the adjoining Jaipur district is sandy. A dam built about 400 years ago had been rendered useless by shifting sand dunes. The village had fallen on bad days-agriculture was negligible lands were barren; and sand was all about, as a result of the strong gusts of wind in the Bhanpur Kalan gap between two parallel ranges of the Aravallis. About 10 years ago, Nathu Lal Gujjar, the representative of the village in the local panchayat (village council), met Nanak Ram of TBS at village Agar. Thus he came in touch with TBS. By then, all his pleas for help to government agencies had failed. The village was about to be abandoned by the residents.

The first thing that TBS assessed was the capacity of the community as well as the organization's capacity to help the village. It then got an idea of the kind of intervention needed to improve the environmental conditions in the village. At Nimbi, the people could have tried to restore the old dam straight away. But the village and TBS jointly decided that it was important to first rehabilitate the smaller dam. The dam was completed much before the schedule, which shows how hard working the people of this village are. And the result was for all to see.

On the other side of the village, an earthen embankment built to connect the breach in the larger old dam to the far end of the valley was built. This earthen structure was built at a cost of about Rs. 500,000[4] (Gopal Singh, 1997). And the result is that crop production in the area downstream of the embankment increased eight times.

iv. Impact of water harvesting on environmental regeneration, agriculture and climate change

I am neither a scientist, nor a professional water engineer nor a climate change expert. I am a small constructive worker of Gandhi and I mobilize the civil society and the community for action on natural resources management and conservation for rural uplift in India. Here I am recording the impact of the above work on the ecology of 6,500 square km area in Alwar district from 1985-2007. Since 1985, 8,600 small water harvesting talabs in 1,068 villages of Alwar district covering 6,500 square km area have been built. This has resulted in the shallow aquifer recharge in ground water bringing up the water table from about 100-120 meters depth to 3-13 meters at present. The area under single cropping increased from 11 per cent to 70 per cent out of which area under double cropping increased from 3 per cent to 50 per cent bringing prosperity to the farmers. The forest cover, which used to be around 7 per cent increased to 40 per cent through agro-forestry and social forestry, providing sufficient fuel wood and sequestering carbon from atmosphere.

The 1,068 villages formed an Arvari Sansad (Arvari Parliament) to frame rules of water use and restricting areas from growing more water consuming crops including paddy. It fixed the rules for pasture use on the basis of rotation. The forest use was limited to lopping of tree braches for fuel or cutting poles for domestic use, but never any tree felling.

I believe this is the way to save the environment and bring prosperity to farmers in Indian villages. Based on this many civil society organizations formed the National Jal Biradari (National Water Federation) to save the Yamuna river. Alwar is a part of the catchment of The Yamuna River, which dries out by the time it passes Delhi, the capital of India. This people's campaign is now in progress.

I invite scientists to estimate the impact of such large community actions on carbon sequestration and fixation. I already know its impact on the rural population. Most farmers who left Alwar for lack of sustenance have already returned to their villages.

Sectoral Allocation and Pricing of Groundwater

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Abstract

This paper highlights the need for moving towards comprehensive management framework for integrated management of all water resources in predominantly agricultural and other rural (where industrialization is being promoted) watersheds and aquifer command areas. It suggests a framework for an allocation policy that will provide rights and entitlements to farmers so as to enable a livelihood above poverty line, an allocation to environment to promote forestation and allocation policy for commercial agriculture and industry. As for framework for pricing policy for industry, this paper suggests taking into consideration various cost factors and approach to determine the respective costs. Different pricing regimes as policy instruments for encouraging efficient water use and enabling cross subsidization have also been discussed. This paper also suggests a framework for a pricing policy for irrigation (through groundwater) that will honor the recommendations of the National Water Policy, 2002 for financial and physical sustainability with respect to recovery of O&M costs and a part of capital costs and transparently targeting the subsidies to the disadvantaged and poorer sections. This paper also suggests a framework for permitting trading of agricultural allocations within the sector and with industrial sector and also suggests safeguards for preventing speculative purchase of water allocations by investors primarily interested in investments in water markets. This paper suggests 7,500 to 15,000 ha as a suitable size for hydrological units for integrated planning and emphasizes the need for comprehensive assessment of all water resources together- surface as well as ground water, for actual quantification of allocations to different users and uses. The need for decision support systems for annual evaluation of water availability and decisions on water allocations to different users and uses has also been emphasized. Gaps in existing groundwater assessment methodologies concerning confined aquifers have been pointed out. This paper further suggests that there should be a national policy to protect aquifers for which the recharge mechanisms are not clear or do not exist, or the recharge durations are very long whereby sustainable exploitation is not feasible. It is also suggested that there should be a national policy to protect natural recharge sites of confined aquifers and that recharge structures should be constructed at such sites to facilitate enhanced natural recharge .Lastly, this paper identifies major roadblocks in the transition process and suggests that a beginning should be made with establishing and demonstrating methodologies for assessment of water resources and creating water access for water users in the poorly endowed areas of hydrological units. It is suggested that a pilot scale national programme may be considered to invite R&D organizations, NGOs and Corporate organizations to demonstrate methodologies for water resource assessment and creating access to poorly endowed users.

Introduction

This paper takes a generic and integrated view of water resources, i.e. surface water resources (including small water harvesting structures to large reservoirs), groundwater aquifers (not including delayed flows that contribute to surface flows in relatively short duration after storm events), infiltrated waters due to surface waters (water harvesting structures and surface flows) that recharge local shallow wells and are use conjunctively, and discharges in the discharge zones of aquifers due to base flows and considerably delayed flows, etc. It is understood that use of surface water is always the top priority of all users and groundwater is used to make up for the shortfall. However, there are considerable large areas where there do not exist significant surface resources and groundwater is the primary source for irrigation as well as industry. The allocations discussed here are based on co-management of surface resources with groundwater resources at the level of local scale watersheds and/or aquifers. This concept of co-management is different from that of conjunctive use. The latter is more or less an extension of surface resource like for example the influence zones of canals and check dams.

Further, so as to address the issue of sustainability, this paper will consider only the groundwater resources where the recharge mechanisms are clear and artificial recharge is possible and cost effective. There should be a national policy on protecting aquifers where recharge mechanisms are absent or recharge durations are too long for sustainable exploitation. There should also be a national policy on protecting natural recharge zones and strengthening natural recharge through recharge structures.

Apart from making suggestions on a framework for groundwater allocations to industry, this paper also explores the possibility of addressing priority issues such as poverty alleviation, food security, maintaining indigenous production base so as to protect the country from adverse international market conditions, etc. through a water allocation policy.

It also needs to be mentioned that the concept of water markets is getting highlighted in policy discussions at various levels. A regime of water allocations can give further impetus to this. However, such initiatives may be premature since we first need to learn to provide and manage allocations, and further create the required institutional mechanisms for regulation before water markets are promoted.

There are studies on informal rural groundwater markets that suggest this is already happening (and therefore the need to formalize it). But the present so called groundwater markets thrive on the fact that groundwater is yet not unambiguously in the public domain and the access to groundwater is purely on the basis of natural endowment conditions. A premature introduction of water markets will give rise to privatization and extreme unsustainable exploitation of a resource which though not in public domain yet is still widely considered as something that should be brought under common property regimes.

This paper will mainly focus on allocations and pricing for irrigation and industry with the bottom line that appropriate allocations have to be created for domestic use and ecology as a top priority. However, in this paper only the allocation to forestation has been discussed briefly as allocation to environment in the rural and predominantly agricultural watersheds and aquifer command areas.

The above position on water markets in this paper not withstanding, this paper also suggests which water rights and allocations are tradable, within sectors and between sectors, and under what circumstances. This should lay the foundation for introducing water market regimes that will allow individuals to choose alternate occupations without foregoing the benefit of water right, provide stimulus to water users to enhance water use efficiencies, and will at the same time prevent privatization of water resources through speculative purchase of water allocations by investors that primarily aim at water trading. Such checks and balances are very essential for a regime of water allocations that has an inherent potential to move towards formal or informal water markets.

Scale of Operation

The size of individual assessment and regulation units will depend upon the surface and subsurface hydrology of a region. But experience in different parts of the country suggests a minimum scale of 7,500 ha to 15,000. But this is just a ballpark figure.
As far as surface hydrology in concerned, the scale should incorporate water harvesting structures up to the level of at least the minor irrigation tanks and the smaller medium irrigation tanks. The water management system may include inter micro watershed water transfers and pumping of water from d/s larger reservoirs in to the u/s smaller reservoirs and recharge structures.

As where subsurface hydrology is concerned this should be based on the pattern of base flows so as to ensure inclusion of perennial water availability areas in the unit along with seasonal water availability areas so that water access can be ensured to all water users and uses all round the year.

Sectoral Allocations

This paper mainly focuses on policy for predominantly agricultural watersheds and aquifer command areas and other rural watersheds and aquifer command areas where industrialization is being promoted and is spreading. It is not the intention to neglect the urban industrial areas where there is, to a lesser or greater extent, dependence on groundwater. However, in such areas the primary issue is not the policy for inter sectoral allocations, the primary issues are curtailing draft, enhancing water use efficiency and high quality wastewater treatment so as to enable recycling and reuse.

Whereas in the rural and agricultural areas the primary issues are protecting agricultural subsistence livelihoods, protecting allocations to industry, protecting drinking water for lean summer months, response mechanisms to temporary water shortages due to deficient rainfalls, wastewater treatment to facilitate use in agriculture and industrial utilities, protecting water resources from contamination, etc.

There is fair amount of clarity in what needs to be done in the urban areas, and doing it is primarily a question regulatory control and administrative will. But in the rural areas where industrialization has already reached some of the adverse impacts are now becoming visible – lowering of water levels, deterioration of water quality, worsening conditions of small and marginal farmers, and so on. Solutions need to be found to the emerging challenges and a coherent policy needs to be developed to enable sustainability and viability of industry as well as agriculture, and also protect the livelihoods of marginalized agricultural households.
Similarly, much attention is also necessary for the predominantly agricultural watersheds and aquifer command areas since there are clear and extreme disparities in terms of water access endowments in such areas. The common refrain among Government and Non Government agencies involved in watershed development and aquifer recharge programmes is "it is up to the people now to pluck the low hanging fruits". This is not acceptable. Some sections are reaping the low hanging fruit due to purely the favorable endowment conditions, and the others are getting further marginalized. This paper suggests policy measures to address this situation too.

Basic Water Rights and Allocations to Farmers as Basic Service

Can rural food security and poverty alleviation be addressed through water allocations as basic right?

The water rights movement in India has not really taken off. The usual refrain among Government as well as Non Government agencies involved in watershed projects is "watershed treatment augments water resources, it is then up to the local people to harvest the low hanging fruits". However, even in micro watersheds, e.g. 500 ha, there are poorly endowed areas (small watersheds on 2^{nd} 3^{rd} order streams) and richly endowed areas in the valley plains. Farmers in the valleys have been reaping the fruits but the farmers in the upper portions are not much better off except perhaps marginal amount of protective irrigation during monsoons. Therefore it is necessary to provide not only an allocation to all families but also clear access mechanisms.

In Maharashtra there has been some amount of water rights movement and some amount of experimentation around this. Presently the basic water right that is being advocated is about 5000 m^3 per ha per year per nuclear family (of about 5-7 members including children and aged). This is considered as sufficient for irrigated cultivation of water efficient crops along with in situ use of rain water on 1 ha. Together (i.e. in situ rain water and applied irrigation) can enable dry biomass production of about 20 to 25 tons per ha and harvest of about 5 to 6 tons of food grains. With voluntary use of irrigation equipment a farmer may be able to cultivate up to 1.5 ha and can therefore go much above the poverty line.

The water rights movement in Maharashtra suggests that such basic water rights should be totally delinked from land ownership so that small and marginal farmers with holding below 1 ha can resort to higher irrigation intensity agriculture of higher value crops. The landless can access lands of larger land holders on suitable terms. Alternately both these categories can trade their water rights.

Since this allocation is basically subsistence allocation the water rates for this should be bare minimum. These entitlements, at least at the initial stage, should not be available for inter sectoral trading with industry since the basic objective of the basic water right is enabling a minimum livelihood on par with poverty line income levels.

While this allocation is primarily aimed at sustainable livelihood of poorly endowed farmers, it will also serve the purpose of ensuring a minimum level of agricultural activity in the hydrological unit if this allocation is allowed trading only within the sector that is agriculture.

Allocations to Environment

Can forestation be promoted through water allocations for environment?

Forest cover parameters (% of land in a watershed that needs to be brought under forest cover) may be fixed on a regional basis and also taking in to consideration green belt requirements of industries. Ideally such plantations should be commercially viable and could be provided allocations from 3000 to 5000 m^3 per ha per year, not including in situ use of rainwater, and can enable production of 15 to 20 tons of dry biomass per ha. This water may be made available to any entities that have water entitlements within the watershed and/or aquifer command area, farmers as well as industries, and are willing to undertake the forestation programme. These allocations should also not be available for trading with other sectors since these are meant to protect the environment, make available biomass for local use (fuel, fodder, wood for housing, energy biomass, horticultural food supplements, etc.), and also for creating supplementary employment opportunities. Non-permissibility of trading with other sectors will encourage private sector to make investments in biomass production and processing, e.g. renewable energy systems, bio fuels, herbal formulations, paper, etc.

Additional Basic Rights and Allocations to Farmers as Economic Service

Depending upon further availability of agricultural land and water (over and above the cultivation possible through the basic water service) further allocations may be made for agriculture. These may be considered as additional basic rights so as to enable farmers to go significantly above poverty line by using this allocation. It is recommended that these allocations may be at economic rates (rates higher than those for the basic service but not the same level as water rates for industry) since water for livelihood security would have already been allocated. In a predominantly agricultural watershed / aquifer command area with higher level of land and water endowment a differential pricing system may also be considered for successive slabs of water allocations. These additional allocations to agriculture may also be tradable rights, including trading with industry. Farmers wanting to take up agriculture in additional lands or wanting to take up water intensive crops may do so using the additional entitlements and may also access more water from farmers who do not use up their additional entitlements. On the other hand farmers who do not want to utilize this allocation, fully or partially, should be free to trade this with industry. This will allow some amount of flexibility in the land and water use choices in a hydrological unit.

Allocations to Industry and Commercial Agriculture as a Commercial Service

This allocation may be considered only after providing above discussed allocations to farmers and environment. Allocations to industry and further allocations to agriculture as a commercial service would be subject to the local agricultural and industrial policy. The water rates for both sectors should be more or less on par since agriculture based on these allocations would be fully commercial agriculture in terms of cropping choices as well as affluence status of farmers. A State Government may choose to provide some degree of concession to either certain types of industries or agriculture depending upon its policy for the region. Where concessions are provided to agriculture, it should be mainly with the objective of promoting agro processing and packaging industry, and therefore directly or directly promoting industrialization.

It is being suggested that economic models need to be developed for taking decisions on such allocations. Such models may take in to consideration various levels of impacts such as –

- Impetus to u/s and d/s economic activity (inputs supply and market linkage)
- Creation of income and employment opportunities for local communities
- Impetus to high quality essential services such as health, education, transport, information connectivity, etc.
- Impetus to services sector
- Additional requirements of water for domestic and other civic use
- and most importantly
- Revenues on water services
- Value addition per unit volume of water for the whole value chain
- Tax returns and revenues to local self government and state and central governments.

The commercial allocations should be allowed trading only on the basis of enhancement of water use efficiency. Trading of unused allocation should also not be permitted. This will prevent an investor from speculative purchase of water allocations and will ensure that the water allocations are directly for productive use.

It is also needs careful consideration that an industry can take some time to reach full production capacity and in the meantime may not be able to fully utilize its allocation. Till such time as it achieves full production capacity the unutilized allocation may be reallocated to other uses and users on annual basis.

Water Resource Augmentation and Management

It may be noted that the proposed model necessitates due attention to water availability and the need for scientific assessment of water resources. The methodology for water resource assessment may be based on following considerations

- Surface flows over the annual cycles
- Potential for surface reservoirs
- Aquifer capacities
- Potential for enhancing recharge at natural recharge zones and also artificial recharge through injection wells
- Hydrological models based on soil and slope conditions, infiltration rates, delayed run-offs, base flows, etc.
- Calibration of run-offs, surface storages and groundwater availability with respect to rainfall vagaries (total rainfall as well as intensity patterns)

It needs to be mentioned and noted that – a) The watershed development programme has so far not comprehensively addressed the issues of techniques for water resource assessment and creating a water rights movement, b) The groundwater assessment by Government agencies is mainly at regional scale and techniques for micro level mapping of aquifers are yet not available, c) The aquifers being addressed by regulatory and technical agencies are mainly water table or phreatic aquifers, and therefore assessment techniques and regulatory mechanisms for confined aquifers are yet not available, d) There is not much clarity on the requirement of ecological stocks in groundwater, and e) the watershed development and aquifer recharge programmes are yet to evolve and adopt a “management” framework, and continue to work with “supply side” approach.

A “management” approach requires a regime of rights and entitlements on the one hand and a decision support system for annual evaluation of water availability, so that decisions on allocations to different uses and users can be taken on year to year basis depending upon post monsoon water availability.

The National Water Policy will come in to play primarily during deficient rainfall years, but this also requires some modification to accommodate the above approach to sectoral water allocation. The modified priorities for rural watersheds and aquifer command areas may be as follows –

- Drinking water
- Basic allocations to agriculturists (farmers as well as landless labor to address food security and incomes on par with poverty line)
- Allocation to environment (to support forestation)
- Additional basic allocations to agriculturists and allocations to commercial agriculture and industry
- Allocation to ecology (surface flows and groundwater stock – requires a scientific framework)

Drinking water will always be the absolute top priority. Next priority would be to support food security and minimum income levels of farmers. Following this priority would be to preserve forests so as to make available essential biomass.

Following the above three top priorities it will be a matter of judicious choices to distribute remaining waters between three types of uses – additional water rights and allocations to farmers, commercial agriculture and industry. Commercial agriculture needs to be protected as much as possible since often this would be perennial and long duration crops (e.g. cotton, sugarcane, grapes, herbs, etc.) that can entail huge losses to farmers if not provided irrigation, and also for protecting the processing and packaging sector, to ensure that it operates at least at the break-even point. Similarly, it is also necessary to ensure that industry also operates at least at the minimum viability level and industrial investments are protected. If possible it is also necessary to ensure additional incomes to farmers so as to enable them to spend on essential services such as health and education and prevent the debt trap.

Institutional Mechanisms

The institutional mechanisms may include at least four types of essential institutions –

- The regulatory authority
- The local Governance institutions
- The local management institutions
- Technical and training support institutions.

Apart from the essential institutions it will also be necessary to have presence of private sector organizations and professionals to provide specialised technical and maintenance services.

The regulatory authority role may include deciding on the basis and quantum of allocations as well as permissible uses for each type of allocation. For example, which types of crops may be made the basis of deciding upon basic allocations, which types of crops are permissible for actual land and water use under basic and additional basic allocations, which types of crops are permissible under commercial allocations, which types of industries are permissible in a particular hydrological unit, etc. The regulatory authority may also be required to adjudicate on disputes among different stakeholders and recommendations by stakeholders and civil society institutions. The regulatory authority may be a central authority (e.g. CGWA) with regional units.

As for Governance institutions, hydrological unit level institutions may have to be created through representation of Panchayats that fall within the units. Hydrological units at the proposed scale will include a number of Panchayats. The Governance institutions may also have representation from Water User Associations of farmers and other stakeholders.

The management institution will have an important role to play – creating water access to all water users and also monitoring of abstraction and use by different users. This agency may have to undertake actually water delivery service to users that are not in a position to manage their own water draft. For example, farmers in the upper portions of watersheds and in seasonal water availability portions of aquifer command areas will have to be provided water access from public or private abstraction structures in the better endowed areas. This will require hydrological unit level water distribution system that is managed professionally.
The technical and training support mechanism may be at the level of clusters of hydrological units and will be responsible for providing the required technical and training support to the Governance and management institutions.

Sectoral Water Pricing

The CGWB has already circulated a policy for pricing. However, the basis of arriving at the proposed values is not yet clear – what are the factors considered in pricing, and the justification of the price/cost value for each factor. The various factors that could be considered in pricing may be – royalty, administrative costs, infrastructure development and O&M for groundwater augmentation or recharge, O&M costs of water abstraction and distribution service, wastewater treatment service, wastewater conveyance service, etc. The additional pricing components could be price as deterrent for excessive use, cross subsidization, opportunity cost, etc., i.e. factors other than direct costs.

Presently of course only the industry is in the price net, agriculture is not being charged. This policy needs to be examined in the context of the recommendations on allocations to farmers and agriculture discussed above. Along with pricing for agriculture the issue of energy tariff for pumping also needs to be discussed.

Groundwater Pricing for Industry

As said above, the CGWB has circulated the pricing policy but the basis for arriving at values is not clear. In this section the pricing factors mentioned above will be discussed in the context of pricing for industry. A number of Central and State agencies are involved in the regulatory, monitoring and management functions and all their costs need to be incorporated in the pricing. But there needs to be a clarity on various cost components and the respective components should go the concerned agencies so that they are able to discharge their functions efficiently.

Royalty

As per the assessment of case law and constitutional and legislative provisions by the Expert Group on Groundwater Management and Ownership (Planning Commission, 2007), Government has regulatory powers so that one user's pattern of use should not affect the rights of other users with respect to quality and quantity. However, the basic right to access groundwater is as per the Indian Easements Act, 1882 and tied to land ownership. Therefore charging of royalty could be legally contentious.

Administrative costs

This may cover costs of regulatory functions, monitoring, etc. A number of Central and State Governments agencies may be involved, e.g. CGWB / CGWA, Central and State Pollution Control Boards, State Water Resources Departments, District Administration, Municipalities, etc. A realistic assessment of costs being incurred by all concerned agencies be made and the respective components should go to the concerned agencies so that they are able to discharge their duties efficiently. This framework also enables a "single window" approach and therefore reduces transaction time and costs. Presently, the CPCB is charging cess on water permits. But it is not clear whether it is towards administrative costs or for providing wastewater management facilities (such as treatment and conveyance). But pricing components towards such services should be assessed separately and charged accordingly.

Infrastructure for Groundwater Augmentation and Recharge

This component may be charged if the Central or State Governments are actually developing infrastructure for groundwater augmentation and recharge, similar to the head works and conveyance systems for surface water management. The National Water Policy 2002 recommends (in the context of financial and physical sustainability) that "There is, therefore, a need to ensure that the water charges for various uses should be fixed in such a way that they cover at least the operation and maintenance charges of providing the service initially and a part of the capital costs subsequently". This recommendation can become a basis for fixing the rates for this component of pricing. Again, this component should go to the agency that is actually executing these activities, i.e. the State water resources departments.

O&M Costs of Water Abstraction and Distribution Service

This issue is hypothetical presently since the Central and State water resources departments are not offering this service in rural areas to industries. But if this service were to be provided then O&M costs and some part of capital costs may become the basis for fixing rates for this component. Again, this component should go to the agency that would be actually executing these activities, i.e. the State water resources departments.

Wastewater Treatment Service

This issue is relevant to mainly small and medium industries. The larger industries using substantial amounts of water are normally mandated to undertake wastewater treatment and therefore discharge only treated wastewater (i.e. if permitted to discharge, since many companies have been mandated "zero" discharge). But the pricing of this service requires careful attention. Treated wastewater can be used in agriculture as also as utilities in industries and residential areas, which could be a revenue generating service to end users. Therefore it is possible that part of the revenue for this service can come from the users of treated wastewater. Therefore industries that want to avail of the wastewater treatment service may be charged in the framework making up for the gap between revenue from treated wastewater users and the actual cost of treatment and redistribution. The service providers for this service may be mainly private agencies. However, usually such projects would be facilitated by State / Central Government agencies, e.g. the industries development corporations. Therefore the revenue movement issue needs to be sorted out, whether the state governments collect the revenue, the central agencies, or the subscribing industries pay directly to the service provider. The National Water Policy 2002 framework for pricing quoted above will be useful for fixing the rates for this service as well.

Wastewater Conveyance Service

This issue comes up when the State Government (through local municipalities) need to provide for the drainage system for conveyance of treated wastewater to the designated river flow or discharge points in the seas. Presently at least the larger water user industries based in rural areas are being mandated to discharge their water at approved points. Therefore this issue also becomes more relevant to small and medium industries.

Other Methods of Water Pricing

Apart from the pricing based on direct costs there are other methods of pricing are also being discussed the world over. These are deterrent to excessive use, cross subsidization, opportunity costs, etc.

The thinking behind the deterrent price is that the price may be kept at a level where the user is compelled to invest on improving water use efficiency. However, while applying this method the impact of this on the competitiveness of the industry needs to be considered. Perhaps the better way would be to persuade industry to improve water use efficiency through dialogue. Other method would be to develop a database on best practices in terms of production per unit water, assess the potential for achieving higher water use productivities under Indian conditions, and put a high price for water use over and above what may be the acceptable use. Government should work with the industry to evolve acceptable norms.

Other method that is often discussed is cross subsidization where pricing of water to industry may subsidise other priority uses. However, this method has the danger of bringing in arbitrariness at the lower end as well as at the higher end. If this method is to be applied then it is first necessary to assess what should be the actual reasonable cost of water service, including the investment costs as well as O&M costs. It is very likely that the high end water user will get charged for the inefficiencies of Government utilities and administration.

Other method that is frequently discussed by economists is opportunity cost which is based on potential benefit to foregone uses. Since in India the top priority is to agriculture the opportunity cost may be assessed with respect to foregone use in agriculture. For example, if 20,000 m^3 per ha is the allocation to sugarcane cultivation and Rs. 50,000 per ha is the projected net income per ha, then the opportunity cost of water would be Rs. 2.5 per m^3. If this method is to be applied then it would be necessary to first assess what should be reasonable, easily achievable water use efficiency, for say sugarcane cultivation, to take this example forward. The desirable water requirement should be significantly lower than the existing level of requirements of flood irrigation, and therefore the opportunity costs should also be much lower than the above example.

However, if opportunity cost is to become the basis of water pricing for industry, then it should be charged only for the amount of water that is lost in industrial use – i.e. productive consumption, losses in conveyance, evaporation losses in storage and evapotranspiration in the green belt. That is, the opportunity cost should be charged only for the quantum total intake minus total wastewater discharge.

Concessions to Industries in Groundwater Pricing

As per the new and emerging groundwater regulation policy industries are being mandated to conduct artificial recharge proportionate to their water requirements. The Quantum of recharge is decided with respect to the level of exploitation in that region. Infrastructure for recharge should get the status on par with surface water infrastructure and if companies are required to invest in the recharge infrastructure they should be given a concession in pricing.

Presently there is another emerging policy where industries are proposed to be provided “groundwater credits” for recharge undertaken over and above the mandatory requirement, and based on the credits top industries will be provided awards. This policy does not appear to be sufficient to motivate industries to undertake additional recharge over and above the mandatory requirement. The groundwater credits should entail direct and assured benefits.

The concept of groundwater credits is clearly seen as a first step towards “markets”. However, such markets will take some time to emerge as it will require a whole institutional mechanism (for evaluation of claims and for regulating the markets) and policy before they can be operationalised. In the mean time there is a necessity for providing assured benefits to such initiatives by companies. This may be in the form of concessions in water rates

Water Pricing for Agriculture

Totally three types of allocations to farmers and agriculture have been discussed above, viz.

- Basic allocation to farmers
- Additional basic allocation to farmers
- Commercial allocation to agriculture

Many State Governments have developed groundwater irrigation schemes for farmers' water user groups. These are usually handed over to the groups so that they take care of O&M. No water rates as such are being charged to farmers. Also that in most states the pumping energy is also highly subsidised. The quote from National Water Policy 2002 given above should become the basis for charging farmers. Therefore the groundwater user groups should be charged –

- At the least a part of the capital costs
- Energy costs in real terms.

The National Water Policy 2002 further recommends (with respect to financial and physical sustainability) that "The subsidy on water rates to the disadvantaged and poorer sections of the society should be well targeted and transparent". The implications of this recommendation require careful consideration while deciding upon water rates to farmers.

First of all it is necessary to have farmers' participation in investments. In the drinking water schemes as also in watershed development and other programmes it is now a well established principal that farmers' participation in investments is necessary for them to undertake the "ownership" of the assets. In the case of groundwater schemes for irrigation such investments result directly in to improved livelihoods and therefore it is appropriate that farmers are charged for capital costs. In the absence of such charge, it is found that many such assets actually benefit only a few farmers, usually the local big-wigs, and many farmers from the group are left out. Many such schemes become defunct since revenue from just a few farmers is not sufficient to cover the maintenance costs. If the farmers were to pay towards capital costs then they would surely struggle for their equitable right so that all the farmers in the group may benefit and there is adequate revenue for maintenance. It may also be considered that there are thousands of private groundwater irrigation systems of farmers where farmers are undertaking all the required investments. Therefore there is not much logic in subsidizing a few farmers.

With respect to the operational costs of groundwater to farmers the cost of energy is the most important factor. In many States the farmers are provided highly subsidized pumping energy. Such subsidies are neither "well targeted" nor "transparent". The water allocation policy to farmers and agriculture being recommended in this paper may be a pointer towards how subsidies can be "well targeted and transparent". If we look at the energy available for distribution as a "pool" of energy generated by different types of sources and the cost of generation (with respect to each type) it may become possible to target subsidies in a transparent manner.

The existing energy sources may be classified on the basis of types and corresponding costs of generation as follows –

- Old hydropower plants
- New hydropower plants
- Old thermal power plants
- New thermal power plants
- Nuclear power plants.

The basic allocation to farmers may be charged on the basis of the lowest generation cost power in the pool (most likely the older hydropower plants), the additional basic allocation may be charged the second or third lowest cost power (most likely the new hydropower projects or the old thermal power projects) and the commercial allocation may be charged at the normal commercial rates, or at the least at the average cost of generation. Even the rates based on the lowest cost power will also be a subsidy shock to farmers, sufficient to stimulate enhancement of water use efficiency in the basic services and perhaps investments in irrigation equipment in the commercial agriculture.

Similarly, the rates for "capital costs" may also be fixed accordingly. The basic service may be charged a suitably low rate towards capital costs, the additional basic service may be charged an intermediate rate, and the commercial service may be charged the same way as non agricultural users are charged. The recoveries towards capital costs may be integrated in the water pricing.

Managing the Transition

The transition from a near total lack of regulation to a regime of allocations is not going to be easy. The biggest stumbling block is going to be the existing groundwater users located in the richly endowed areas that have been having unrestricted access to water, and also perhaps indulging in the so called informal water markets.

One can anticipate that there will be a very volatile opposition. Many will also take legal recourse, terms such customary rights will be used. Government's powers to evolve a regime of allocation (and pricing) may be questioned. In the end power tariff and recoveries over investments on water resource augmentation may become important tools for bringing in water use discipline and freeing water for reallocation.
A realistic power tariff will itself become a deterrent to excessive use. Therefore it is important that the Government takes a fresh look at the power tariff to agriculture and considers the recommendation on the same made in this paper.

The tool of power tariff alone may not be sufficient. It may also become necessary to bring in a policy on irrigation efficiency and facilitate water saving through public and private investments – literally speaking buying back water through such investments. It may also become necessary to strengthen the legal position of the Government through legislative changes that support equitable water rights, at the least in a limited send within the bounds of a hydrological unit.

But on the flip side the Government is going to earn lot of goodwill from the poorly endowed farmers and they may become willing participants in the initial trials and errors and various participatory processes. The first step towards transition will be establishing and demonstrating methodologies for assessment of water resources and creating access to users in poorly endowed areas, and these activities will require much informed participation of the local people.

Conclusion

This paper highlights the need for moving towards comprehensive management framework for integrated management of all water resources in predominantly agricultural and other rural (where industrialization is being promoted) watersheds and aquifer command areas. It suggests a framework for an allocation policy that will provide rights and entitlements to farmers so as to enable a livelihood above poverty line, an allocation to environment to promote forestation, and allocation policy for commercial agriculture and industry.

The allocation policy suggested in this paper has potential to address priority issues such as poverty alleviation, environment rehabilitation, promotion of commercial agriculture and d/s value chain, and also sustainable promotion of industrialization so as to enable a balanced economic growth of the hydrological units, with the hope this will also bring in a services sector with good quality services and essential services such as health and education.
This paper also suggests a framework for a pricing policy for irrigation (through groundwater) that will honor the recommendations of the National Water Policy 2002 for Financial and Physical Sustainability, viz. "*….that the water charges for various uses should be fixed in such a way that they cover at least the operation and maintenance charges of providing the service initially and a part of the capital costs subsequently…… The subsidy on water rates to the disadvantaged and poorer sections of the society should be well targeted and transparent*".

As for framework for pricing policy for industry a framework that takes in to consideration various cost factors and approach to determining the costs. Different pricing regimes as policy instruments for encouraging efficient water use and enabling cross subsidization have also been discussed. It is also being suggested hat the pricing policy for industry should be evolved through dialogue with industries where various costing factors and policy imperatives may be discussed transparently.

This paper also make suggestions on trading of allocations, which allocations are allowed trading within the sector (namely agriculture), and between sectors (that is agriculture and industry). Safeguards for preventing speculative purchase of water allocations by investors primarily interested in investments in water markets have also been suggested.

This paper also emphasizes the need for demarcation of hydrological units and for comprehensive assessment of all water resource together, surface as well as ground water, for actual quantification of allocations to different users and uses. Gaps in existing groundwater assessment methodologies concerning confined aquifers have also been pointed out. This paper further suggests that there should be a national policy to protect aquifers for which the recharge mechanisms are not clear or do not exist, or the recharge durations are very long whereby sustainable exploitation is not feasible. It is also suggested that there should be a national policy to protect natural recharge sites of confined aquifers and that recharge structures should be constructed at such sites to facilitate enhanced natural recharge.

Lastly this paper also outlines some of the important roadblocks in the transition process and suggests that a beginning should be made with establishing and demonstrating methodologies for assessment of water resources and creating water access for water users in the poorly endowed areas of hydrological units. Perhaps a pilot scale national programme may be considered to invite R&R organizations, NGOs and Corporate organizations to demonstrated methodologies for water resource assessment and creating access to poorly endowed users.

Ground Water Management in Coastal Areas

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Abstract

India has a very long coast line which is the backbone of its national economy. Three out of the four metros, the major industrial hubs, about one fourth of the country's population and the most fertile agricultural land are situated in this area. This is the region where natural calamities like tsunami; cyclones etc frequently affect the normal life. The coastal region occupies some of the most potential aquifer systems of the country. The coastal aquifers of India ranges from that of Jurassic to Recent and is seen almost all along the coast right from Gujarat to West Bengal. Some of the aquifers especially the Tertiary to Recent ones are highly potential and are developed extensively. The small island aquifers of Lakshadweep are highly sensitive since fresh water is seen floating as a thin lens over sea water here. The problems are also complex in the coastal area. Some of them are sea water intrusion, salinity from the aquifer (in situ) material, pollution, global warming and its impact on these aquifer systems. The hydogeological scenario of the coastal area is discussed briefly in the paper. Sea water intrusion is reported in Gujarat and Tamil Nadu and the salinity in other areas are mostly derived from the aquifer materials. The sea level changes in the past and the present day sea level rise due to global warming and the impact on the coastal aquifers especially that of the small island aquifers of Lakshadweep are discussed in detail. The paper also discusses the details of these problems, remedial measures and how it is going to affect the aquifers of the coastal areas of country.

Introduction

India has a very long coastline and 25% of the country's population lives in the coastal zone. Similarly, urban centers are located mostly along the coast when compared to other parts of the country and three out of the four metros are located on the coast. The coastal zone is the most industrialized area in the country. Fourteen major, forty four medium and fifty five minor rivers/streams discharge into the sea through the entire length of the coast. The eastern coast is much wider than its western counterpart and the Arabian sea water is more saline compared to the Bay of Bengal. This is due to the high evaporation combined with low river discharge along the western coast.

The high population density along the banks of major rivers and coastal areas is attributed to the easy availability of water. The search for ground water also began along the alluvial tracts of rivers and coastal areas. The semi consolidated and unconsolidated sediments along the coastline helped mankind to go in for deeper groundwater exploration during the first half of the last century. As the exploration advanced towards deeper horizons, problems like salinity hazard, salt water intrusion, land subsidence etc. were faced, which made the situation quite complex. The high population and the modern living standards demand more water, which has put the coastal aquifers under stress. Most of the coastal aquifers are sedimentary in nature, with a few out crops of hard rocks along the coast.

Hydrogeological Set up

One of the important features of the coastal deposits is the occurrence of ground water in the inter-bedded alluvial and marine sands, silts, clays and carbonate rocks deposited under beach, lagoonal, estuarine and marine environments. Coarse sediments are found to occur along the coast where youthful rivers discharge. Generally due to the differential compaction and the nature of the bedrock topography, the coastal sediments attain a seaward dip. All these factors have a control on the quality of the formation water. The coastal configuration and land forms vary widely depending upon the intensity of wave action, tides, other currents, sediment load, stage of the rivers, wind action and the ever changing riverine regime. The shorelines can be straight or irregular depending upon the structural features and wave energy. The delta formation along the river mouths has also an important role in the coastal hydro geologic scenario. The distribution of fresh water aquifers is controlled by the dynamic equilibrium between hydrostatic heads in the fresh and saline water zones, in flux of sea water into the streams and lagoons and the relative mound of sea with respect to the land mass.

Factors Affecting the Coastal Aquifers

Coastal sedimentary aquifers are among the most productive aquifers and due to this the stress on them are also more. Caution needs to be exercised while developing these aquifers, as over development can result in various adverse environmental impacts including seawater intrusion and land subsidence.

Land Subsidence

Large scale of withdrawal of ground water, especially from the artesian aquifers can sometimes result in land subsidence due to compression of the aquifers. Land subsidence poses serious problems to buildings and other structures. Sometimes this causes inundation of low lying areas, resulting in sea water ingress. The subsidence depends on the nature of sub surface formations, their extent, magnitude and duration of the artesian pressure decline (Karanth K.R., 1987).

Sea Water Intrusion

When groundwater is pumped from aquifers that are in hydraulic connection with the sea, the gradients that are set up may induce a flow of salt water from the sea toward the well. The migration of salt water into freshwater aquifers under the influence of groundwater development is known as *seawater intrusion*. There is a tendency to indicate occurrence of any saline or brackish water along the coastal formations to sea water intrusion. The salinity can be due to several reasons and mostly it can be due to the leaching out of the salts from the aquifer material. In order to avoid mistaken diagnoses of seawater intrusion as evidenced by temporary increases of total dissolved salts, Revelle recommended Chloride-Bicarbonate ratio as a criterion to evaluate intrusion (Mercadeo A, 1985). In India, sea water intrusion is observed along the coastal areas of Gujarat and Tamil Nadu (Thambi D.S. 2010).

Upconing of Saline Water

When an aquifer has an underlying layer of saline water and is pumped by a well penetrating only the upper freshwater portion of the aquifer, a local rise of the interface below the well occurs. This phenomenon is known as upcoming. The interface is generally near horizontal at the start of pumping. With continued pumping, the interface rises to progressively higher levels until eventually it reaches the well. This generally necessitates the well having to be shut down because of the degrading influence of the saline water. When pumping is stopped, the denser saline water tends to settle downward and to return to its former position.

Upcoming of sea water is reported from the Lakshadweep and other small islands (Thambi D.S. 2009). In these islands, the fresh water floats over saline water as a thin lens and for every drop one unit of the fresh water level the saline water rises by forty units. Due to this, the islands do have very fragile ground water system and no pumping can be recommended here. The fresh water has to be skimmed to avoid upcoming.

Geogenic Salinity

This is the most common quality problem observed in the coastal aquifers. Here the salinity is due to the leaching of the salts in the aquifer material. In some cases, the formation water gets freshened year after year due to the leaching effect. A case study from Kerala is discussed in the later part of this paper.

Pollution

Rivers are the major contributors of pollution of the coast and coastal aquifers. Almost all the rivers in our country are polluted mostly due to sewerages and industrial effluents.

Sea Level Rise

The anticipated sea level rise due to global warming poses a serious threat to the coastal aquifers, especially the small island aquifers. The rise in the sea level will push the fresh water seawater interface more inland along coastal aquifers and will submerge low lying areas with sea water, thereby making the shallow aquifers saline. The small Lakshadweep islands will be the worst affected by sea level rise.

Hydrochemical Case Studies from Kerala

Detailed hydro chemical studies carried out in Kerala had revealed very interesting results on the source of salinity and the change of ground water type geographically. Some of them are discussed below.

Warkali aquifers – Change in geochemical type

The change in the degree and type of mineralisation of the water in this aquifer can be explained as a reflection of the different stages of the interaction of the recharging fresh water with the sediments deposited under marine environment.

Initially, Ca – HCO_3 type water was formed by the chemical action of rain water, containing carbon dioxide, on Calcium Carbonate bearing minerals along the recharge area. The Calcium rich water, during its movement, releases Sodium by ion exchange from clay minerals (under marine conditions the clay minerals are sodium rich). This results in Na – HCO_3 type water. The higher content of Fluoride in this area is also due to this reason (CGWB 1992). The alkaline water depleted in Calcium is effective in releasing fluoride from minerals like fluor-apatite. Further north, where the freshening is incomplete, hard brackish water of Ca-Mg-Cl or Na-Cl type occurs. Similar situation is observed in Sweden as well (Agerstrand et.al. 1981)

Isotope Studies

Studies on the ^{18}O content were carried out to know the source of brackishness in ground water in the Tertiary aquifers. A rain water sample, 14 shallow ground water samples from the recharge area, 31 ground water samples tapping the deeper Tertiary aquifers and a sea water sample were subjected to analysis. Chloride is chosen as the parameter indicative of evaporation processes leading to the fractionation of isotopes and also indicative of mixing of saline and fresh waters. The data plot at the first stage shows an increase in both Chloride and ^{18}O indicating the evaporation processes. The second is a rise only in Chloride whereas the ^{18}O has stabilized at about –2 per mil. The evaporation stops at depth and hence there is no further increase of ^{18}O whereas the saline pore waters of the clay layers continue to diffuse into the formation waters thereby increasing the Chloride content. Analysis of a clay sample from a borehole indicated Chloride content of 660 mg per kg of dry clay. The Chloride content of the pore water was calculated to be around 2000 mg/l (Jacks 1987). Mixing of sea water, if any, shall show an increase in the trend of both Chloride and ^{18}O.

The isotope studies thus indicate that the brackishness in parts of the Tertiary aquifers of Kerala is not due to mixing of sea water but due to the diffusion of salinity from the intercalating clay beds.

Freshening process

The quality of water in the Tertiary aquifers indicates that the relative concentrations of the major ions and trace elements are different from that obtainable by sea water dilution/ mixing. Detailed studies indicate that a freshening process is occurring in the aquifers. One of the parameter to indicate the long term process of freshening or sea water intrusion is the Na/Cl ratio (Jacks 1987 and Mercadeo 1985). In the course of sea water intrusion, part of the Sodium ion is exchanged for Calcium and Magnesium ions, which are the predominant cations in the exchange sites of clay minerals in the fresh water aquifers. The resulting water will be depleted in Sodium. The Chloride ions continue to remain in solution, since Chloride does not undergo ion exchange, precipitation, complexing, oxidation, reductions or biological reactions (Hem J.D. 1970). Thus, the Na/Cl mole ratio during intrusion shall be less than 0.85, the mole ratio in seawater. When freshening of saline aquifers occurs, the direction of the cation exchange is reversed and the opposite trends will be effective and the Na/Cl ratio will be higher than that in seawater. It is seen that the Na/Cl ratio for most of the water samples is higher than that of sea water fresh water mixing and majority of them fall in the field of freshening

Management of Coastal Aquifers

The coastal aquifers have to be managed carefully and cautiously to avoid problems like sea water intrusion and land subsidence. For this, detailed studies and regular monitoring are required.

- The aquifer geometry, distribution of the fresh water and saline water in the system has to be studied in detail.
- Constant monitoring of the pumping, movement of the fresh water saline water interface are to be carried out.
- Tidal influence into the aquifer has to be studied in detail and is to be monitored periodically.
- Safe yield of the aquifer has to be evaluated and accordingly the extraction has to be restricted.
- Remedial measures have to be done wherever sea water intrusion has taken place.

Some of the policy matters are discussed below in brief.

- Finding alternate source of water or other suitable remedial measure wherever serious ground water problem exists.
- Impose restriction for ground water withdrawal along over exploited, critical and other problem areas.
- Mass awareness/ mass interaction programmes shall be conducted to educate the masses and also to understand their problems.
- Preparing a policy document for the judicial and equitable distribution of the resource.
- Creating a buffer zone along the coast wherever there is a possible threat to the aquifers.
- Incorporate necessary measures required in the Coastal Regulation Act.

Regulations Needed

The regulations needed or to be considered in the coastal area are entirely different from those of other areas. In other words, these regulations are to be seen in a different perspective. In an over exploited area, regulation can be imposed once the over exploitation is confirmed whereas in a coastal area nobody can wait for something to happen since by that time the entire aquifer system would have been destroyed. In many cases, the restoration of such aquifers back to normal is either impossible or highly costly. Under these circumstances, prevention is better than cure. The regulations, that can be considered for implementation, are precaution/ prevention; control/ restriction and remedial measures/ restoration.

Precaution is the best way of approaching the problem. By constant monitoring, precautions can be taken at the right time to avoid any type of future problems. Prevention starts where precaution ends. Certain regulations have to be implemented to prevent any untoward happenings in future and this will be the preventive measure.

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Ground Water Management in Alluvial Areas of Punjab

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Abstract

Alluvial formations are important sources of abundant and dependable ground water supplies. Because of large saturated thickness and high well yields, these formations have been extensively exploited for large-scale supplies of water for industrial, irrigation and urban use. Intensive use of ground water from these formations has led to several problems. Such is the case in Punjab also. Despite the fact that Punjab occupies only 1.57% geographical area of India, it contributes more than 50 % grain in the central grain pool. More than 83% of land in Punjab is under agriculture as compared to 40.38% of national average. The cropping pattern of wheat and paddy rotation has led to manifold increase in irrigation water demand. Injudicious surface water irrigation policies, indiscriminate / excessive ground water pumpage due to free electricity coupled with irrational irrigation and agricultural practices have led to situation wherein fresh ground water resources of the state have depleted at an alarming rate in most parts of the state. On the other hand, the south-western parts of Punjab are facing severe water logging problems. Thus the state has to have a twin pronged strategy to manage its ground water resources – i) to arrest the declining trend of ground water and ii) to combat water logging.

Punjab is occupied by Quaternary alluvial deposits of Indus river basin. In major part of the state, ground water levels are in the range of 10 to 20 meters. However around major cities like Jalandhar, Ludhiana, Patiala, Amritsar and Sangrur, water levels are 20 to 40 meters deep. The long-term water level fluctuation data indicates that water levels in major parts of the state have declined drastically. As per the ground water assessment carried out, net dynamic ground water resources of Punjab State are 21.443 MCM (Million Cubic meters), whereas net draft is 31.162 MCM, leading to ground water deficit of 9.719 MCM. The stage of ground water development for the State as a whole is 145% and the State falls under “over- exploited” Category.

Apart from several water management strategies, like better irrigation and on-farm management practices, change in cropping pattern, banning early plantation of paddy etc., the main emphasis in this paper has been laid on the utilization of non-committed surplus monsoon rainfall runoff. As per the Master Plan for artificial recharge to ground water prepared for Punjab state, about 1200 MCM of water is available from surplus monsoon runoff. By adopting rain water harvesting and artificial recharge to ground water by utilizing this water, the negative impact on the ground water regime can be checked, to quite an extent. Central Ground Water Board has taken up several pilot demonstrative artificial recharge projects in Punjab that can be replicated in other parts of the state too. Some of these projects have also been discussed in this paper.

General Features

Punjab State, located in northwestern part of India, has an area of 50,362 sq.km. which constitutes 1.57% of total area of country. The economy of the state is primarily agro based. The state falls in the Indus basin and is drained by three major rivers - the Ravi, Beas and the Sutlej apart from other drainage channels including the Ghaggar that drains the southern parts. In Punjab state about 85% of geographical area is under agriculture. It has a cropping intensity of 184%. Traditionally, the farmers had followed the Maize-Wheat or Sugarcane-Maize-Wheat cropping pattern but during last about four decades, they have shifted to Wheat-Rice cropping pattern thereby leading to increased demand on irrigation water. There were only 1.92 lac shallow tube wells in the State, during the year 1970, which increased to 6.00 lac in 1980, and presently there are more than 10 lac tube wells in the state.

Ground Water Regime

Aquifer System

Almost 90% of the state is underlain by Quaternary alluvial deposits except the northeastern part that is occupied by Tertiary formations outcropping as Siwalik Hills. The fluvial deposits of the Ravi, Beas and Sutlej rivers have formed the alluvial plains. The quaternary deposits are divided into:

(i) Piedmont deposits occurring along a narrow belt along the Siwaliks locally known as "Kandi";
(ii) The alluvial plains which are the most important ground water reservoir;
(iii) Aeolian deposits occurring in the southwestern part of the State; and
(iv) An intermontane valley near Anandpur Sahib in Ropar district.

Based on exploratory drilling carried out by Central Ground Water Board down to about 450 meters below ground level in a major part of the state, it has been deciphered that thick fresh water aquifers exist throughout the State and are laterally and vertically extensive and persistent in nature. However, in southwestern parts, the thickness of fresh water aquifer is much less as compared to the other parts because area is underlain by brackish / saline water. The thickness of fresh water sediments barring southwestern part is more than 350m (explored depth). In northeastern part of the State the thickness of fresh water sediments is greater than 450m (explored depth). In southwestern part the thickness of fresh water sediments varies from 10 to 200m, it decreases towards extreme southwestern corner of the State where it is less than 10m.

The following aquifers zones have been delineated in the state based on the yield characteristics of the aquifers.

i) Local and discontinuous, fairly thick aquifers having fresh water down to 50 meters with average yield of wells below 50m^3/hour covering an area of about 12,000 sq.km. in Faridkot, Moga, Bathinda, Mansa, southern parts of Sangrur and Ferozepur districts.

ii) Regionally extensive and fairly thick aquifers down to 300 meters with an average yield of wells between 50 – 150 m^3/hours occur in a narrow strip extending from south of Fazilka to north of Moga and also in the north eastern parts of Gurdaspur, Hoshiarpur, Nawanshahar, Patiala, Ropar districts and Anandpur Sahib valley of Ropar district. This comprises an area of about 7000 sq.km.
iii) Regionally extensive and fairly thick aquifers down to 450 meters with an average yield of wells above150 m^3/hour occur in an area of about 29,000 sq.km. covering whole of Amritsar, Kapurthala, Fatehgarh Sahib, Ludhiana, Patiala districts and parts of Sangrur, Gurdaspur, Ferozepur, Patiala, Nawanshahar, Jalandhar and Ropar districts.
iv) Hilly terrain of about 2000 sq.km. in parts of Ropar, Gurdaspur, Hoshiarpur and Nawanshahar districts is underlain by semi-consolidated formations having limited yield potentials below 50 m^3/hour except plateau area (beet area) in Garhshankar block of Hoshiarpur district which has yield potential of 100m ^{3}/hr to 200 m ^{3}/hr.
v) Auto flow area – mostly in Gurdaspur district along the right bank of the Beas and Chaki khad and along left bank of the Ravi and Anandpur Sahib block of Ropar district. The artesian flowing aquifers occur generally below 40 metres depth and along left bank of Ravi river up to 155 m.bgl. The free flow discharge ranges between 1 to 70m^3/hour.

Ground Water Level Behavior

The depth to ground water in a major part of the state ranges between 10 to 20mbgl except in the southwestern part where it is less than 5 mbgl. Depth to water level is more than 20mbgl around major cities like Jalandhar, Ludhiana, Amritsar, Patiala, Fatehgarh Sahib, Nawanshahar and Sangrur. Water levels deeper than 50 m occur in the Plateau region of Garshankar Block of Hoshiarpur district. Out of 50,362 Sq.km area of the State, 39,000 Sq.Km area (78%) shows a decline in water levels. The decadal fluctuation in water level show fall in water levels is between less than 2 meters to more than 4 meters.

Ground Water Resources

Groundwater resource estimation of Punjab state has been carried out as per GEC 1997 methodology. The last assessment of ground water was carried out as on 31.3.2004. According to this assessment, net ground water resources of Punjab State are 21.443 BCM, whereas net draft was 31.162 BCM, leading to ground water deficit of 9.719 BCM. The stage of ground water development for the State was 145% and the State as a whole falls under "over exploited" Category. The following table-1 gives district wise ground water resources:

Table-1

District	Net Annual Ground Water Avail-ability (ham)	Existing Gross GW Draft for irrigation (ham)	Existing Gross Draft for domestic and indust-rial (ham)	Existing Gross GW Draft for all uses (ham)	Allocation for domestic, industrial use for 25 years (ham)	Net G W Avail-ability for irrigation developme nt (ham)	Stage GW Develop-ment (%)
AMRITSAR	246120	366699	6275	372974	9121	-129701	152
BATHINDA	85349	78412	680	79093	712	6225	93
FARIDKOT	51109	54056	220	54277	266	-3214	106
F.GARH SAHIB	52566	83552	1021	84573	1483	-32468	161
FEROZEPUR	219383	228769	2367	231136	3570	-12956	105
GURDASPUR	185256	193600	4097	197697	6072	-14416	107
HOSHIARPUR	91817	74603	3536	78139	4575	12640	85
JALANDHAR	113203	257084	30033	287117	31336	-175217	254
KAPUR-THALA	62156	124929	1972	126901	2580	-65354	204
LUDHIANA	234117	323274	14816	338089	17201	-106357	144
MANSA	80421	140412	30	140442	30	-60021	175
MUKTSAR	84328	51990	160	52150	160	32178	62
MOGA	122039	214540	2128	216668	2636	-95137	178
NAWAN SHAHR	66480	114933	1208	116140	1517	-49971	175
PATIALA	163087	264951	3602	268553	5236	-107099	165
ROPAR	58645	47717	6743	54460	7881	3047	93
SANGRUR	228216	414055	3688	417744	5266	-191106	183
TOTAL	**2144292**	**3033577**	**82575**	**3116152**	**99641**	**-988926**	**145**

Out of 137 blocks of the State, 103 blocks are over exploited, 5 blocks are critical, 4 blocks semi critical and 25 blocks are in safe category. The safe category blocks fall all along the foothills where water levels are deep or in the southwestern part of the state where water logging occurs or water is not potable. A map showing ground water development in Punjab(Fig-i) has been prepared.

Ground Water Management

In the state of Punjab, there are several problems that are associated with ground water. Whereas a greater part of the state is facing declining ground water levels due to over-exploitation of the resource, some part is facing rising water levels and concomitant water logging. There are cases of pollution of ground water due to various human activities as well as shortage of clean drinking water in urban areas. Some of the major issues that need to be addressed are outlined below:

1. Ground Water Depletion Due To Overexploitation
2. Rising Water Table and Water Logging
3. Saline / Brackish Water – Use and Disposal
4. Flood Plains – Scope For Ground Water Development
5. Water Shortage In Urban Areas
6. Ground Water Development in Hilly Areas
7. Ground Water Pollution

In the overexploited areas, mainly resorting to artificial recharge and following various conservation practices can augment ground water. The conservation would include: Increasing water use efficiency ,change in cropping pattern, change in irrigation policy, timely plantation of paddy, promotion of sprinkler and drip irrigation, realistic irrigation power pricing, mass awareness program, ground water regulation and recycling of water.

In this paper only ground water management strategy for overexploited areas by artificial recharge has been discussed.

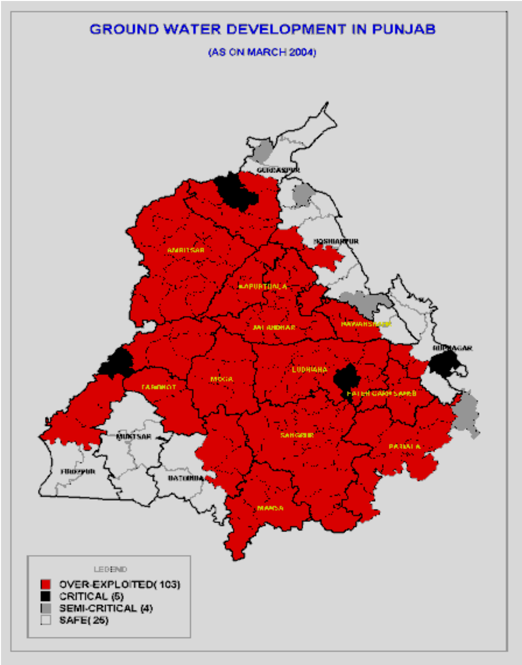

Fig-1. Ground water development in Punjab

Artificial Recharge to Ground Water

Master plan for artificial recharge to ground water has been prepared for Punjab state. Punjab state is endowed with good surface water resources. Master plan for artificial recharge to ground water has been prepared as follows:

i) Identification of area suitable for artificial recharge to ground water,
ii) Estimation of subsurface storage space and quantity of water needed to saturate the unsaturated zone,
iii) Quantification of surface water requirement and surplus runoff available for artificial recharge in each district,
iv) Working out suitable recharge structures, their numbers, and capacity to recharge with available resource.

The area feasible for artificial recharge has been demarcated on the basis of depth to water level and declining trend. In the state 26,650 km^2 area has been identified for artificial recharge, where water levels either have declining trend or are deep and sufficient thickness of vadose zone is available to store the recharged water. The area lies mainly in Amritsar, Kapurthala, Jalandhar, Ludhiana, northern parts of Ferozepur, Moga, Sangrur , Patiala and small parts of Ropar and Nawanshahar districts extending in a north west to south east direction. Based on the area suitable for artificial recharge and thickness of vadose zone, it has been computed that about 18,866

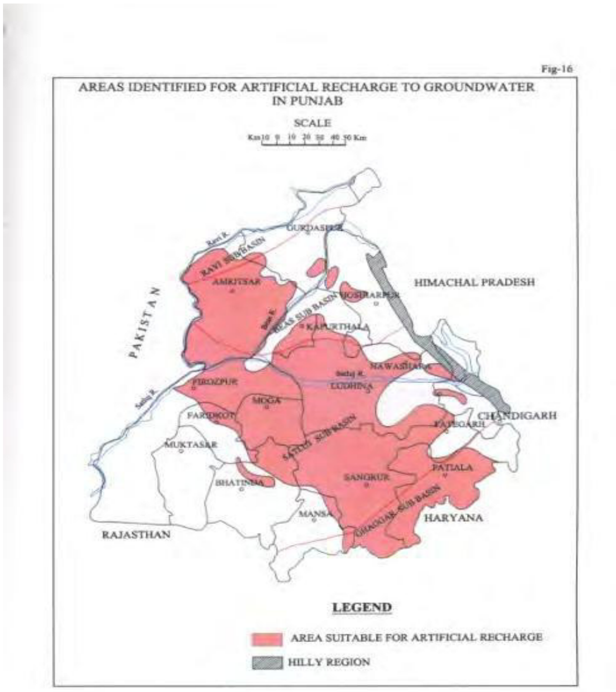

Fig2. Areas identified for Artificial Recharge to ground water in Punjab

MCM of sub-surface storage potential exists below 3 meter below ground level which can be utilized to store additional water through artificial recharge. Total water required for saturating this dry zone has been assessed keeping in view the fact that the average recharge efficiency of artificial recharge structures is about 75% only. Thus, to arrive at the total volume of source water required at the surface, the unsaturated space is multiplied by 1.33(reciprocal of 0.75). Thus the total source water requirement works out to be 25089 MCM. The basin wise estimates are given in table-2:

Table-2 Surface water availability for Artificial Recharge

S.No.	Name of sub basin	Area identified for artificial recharge (Km^2)	Sub- surface storage potential (MCM)	Surface water requirement (MCM)	Proportionate non - committed water resources available (MCM)
1	RAVI	1500	1053	1401	228.7
2	BEAS	4800	3645	4848.50	448.70
3.	SATLUJ	16450	12702.50	16893	293.80
4.	GHAGGAR	3900	1463	1946	229.70
	TOTAL	**26,650**	**18,863.5**	**25,088.5**	**1,200.9**

However, it is very important that only non-committed water resources are considered for artificial recharge in the state. These have been estimated as 1201 MCM. Artificial recharge schemes by using surface run-off in drains and spare canal water during lean period for augmentation of ground water can be taken up for arresting the declining water table. Artificial recharge of surface runoff needs to be planned by providing long trenches with recharge wells in the drains, constructing low height dams in the bed of choes in Kandi area, improving the watershed management in rural areas for arresting the wasteful runoffs during rains and channelizing these in village ponds and other local depressions. Spare canal water during monsoon may be injected into the ground through recharge wells, dug-cum-bore wells, cavity wells, existing ponds may be cleaned and deepened to increase the recharge through pond beds or shaft-cum-recharge wells may be constructed on sides of ponds.

Central Ground Water Board has carried out 21 pilot projects for artificial recharge to ground water in the state of Punjab. These projects were under taken in Amritsar, Jalandhar, Kapurthala, Ludhiana, Moga, Patiala, Sangrur, and Ropar and Patiala districts. Artificial recharge projects were under taken by utilizing surplus canal water, utilizing runoff in the drains, through village ponds, and rooftop rainwater. Recharge structures feasible are, dug cum bore well, modifying the drain bed, vertical and lateral trenches, recharge wells and check dam. Some findings of pilot artificial recharge projects are as follows:

Artificial recharge to ground water at Bhattian Canal Colony, District Ludhiana

Stage of ground water development of Khanna block of Ludhiana district is 194 %, highest in Ludhiana district as on 31.3.2004. Artificial recharge scheme was undertaken at Bhattian Canal Colony, village Bhattian, district Jalandhar utilizing surplus canal water of Khanna distributary, which originates from Samrala distributary of Bharka main line canal. It is observed that farmers rely more on ground water extraction through tube wells as it is readily available throughout the year in their own lands. The water from canals and distributaries goes waste during non showing season and monsoon period. The scheme aims to recharge the ground water by utilizing surplus water of Khanna distributary.

The water levels of Khanna area show a decline of 2.60 meters from year 1991 to 2002 (during the period of study). Thus water levels are declining @ 21 cm /year. The dry zone in the area extends up to 15 meters. By excluding top 3 meters not to be recharged to avoid water logging condition, the remaining 12 meter of dry zone has de-saturated aquifer material having a volume of 60 MCM.

Subsurface geological formations of the area are top clay mixed with fine sand and silt layer up to a depth of 4.5 meters, followed by medium to fine sand up to depth of 40 meters. One distribution tank of 5m x 4m x 3 m was constructed to divert the surplus canal water. To connect the distribution tank with canal, 10 m long R.C.C. pipe of 225 mm dia was laid(Fig-3)

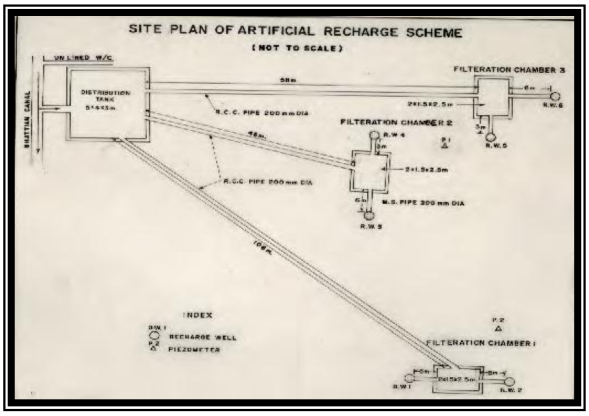

Fig-3. Site plan and construction of Artificial Recharge structure

From distribution tank, the desilted water was fed into three filtration chambers of size 2m x 1.5m x 2.5m each through 200mm dia RCC pipes of length 58m, 46m and 108 meters. The filtration chambers connected to a set of recharge wells through MS pipe of 200mm dia of varying length .In order to inject canal water under gravity into the unconfined aquifer system, 6 recharge wells were constructed at different locations. Two piezometers (observation wells) were also constructed to monitor the impact of recharge on ground water. The recharge wells were constructed to a depth of 31 to 35 meters by tapping aquifers below 24 meters. The water for artificial recharge has been diverted from the distributary by providing 2 RCC pipes of 225 mm (9" dia) and 101mm (4") dia . As no regulator has been provided for regulating water to the recharge structures, hence during the period of canal running days, the water will be automatically diverted in to the distribution tank and after passing through filtration chambers recharge the unconfined aquifer through six recharge wells. The canal runs on an average 167 days in a year and volume of canal water available for recharge is 952301 m^3 with an average discharge rate of 66 lps.

In order to assess the impact of recharge on ground water , water from canal at a rate of 5702m^3/day (@ 66 lps) was recharged through six recharge wells. The water was recharged from 1st July 2002 to 31st Jan, 2003. During the period water was available for 118 days. The volume of water was recharged varies from 34214m^3 (Oct.2002) to 1,65,370m^3 (Aug,2002).

Artificial recharge to ground water in Patiala Nadi, District Patiala

Artificial recharge scheme was undertaken in the bed of Patiala Nadi, in between village Kalwa and Daun Kalan in Patiala district. Patiala district is one of the overexploited district of Punjab with stage of ground water development as 165 % (as on 31.3.2004). The ground water development of Patiala block is 188 %. The depth to water level of the area during the period from 1994 to 2000 shows decline of water levels by 2.65 meters, indicating a fall of 0.43 m/year. Subsurface geology mainly constitute top covering clay layer followed by fine to medium sand down to depth of 26 meters.

The study area(Fig-4) is divided into three slices. In slice I & II, twenty trenches of 10 m in length, 3 meter wide and 3 meter in depth with one recharge well of 26 meter depth in each trench were constructed. In slice III, one lateral trench of 125 meter in length with 5 recharge wells was also constructed. The recharge wells were constructed at a distance of 25 meters from each other. The trenches were filled with inverted filter. Piezometers were also constructed on either side of the Patiala Nadi. Four sets of rectangular weirs to monitor the discharge in Patiala Nadi were constructed.

Recharge impact assessment was carried out in October 2002 and August 2003. Discharges were measured through rectangular weir in the upstream and down stream of trenches. It is observed that in small trenches with recharge wells the discharge at upstream was 3560 lit/sec whereas at downstream it was 3350 lit/sec. It was assessed that water was recharged in twenty recharge structures at the rate of 210 lit/sec with the intake capacity of each recharge structure as 10.5 lps. In the lateral trench the recharge rate was 6.4 lps/running length of the trench.

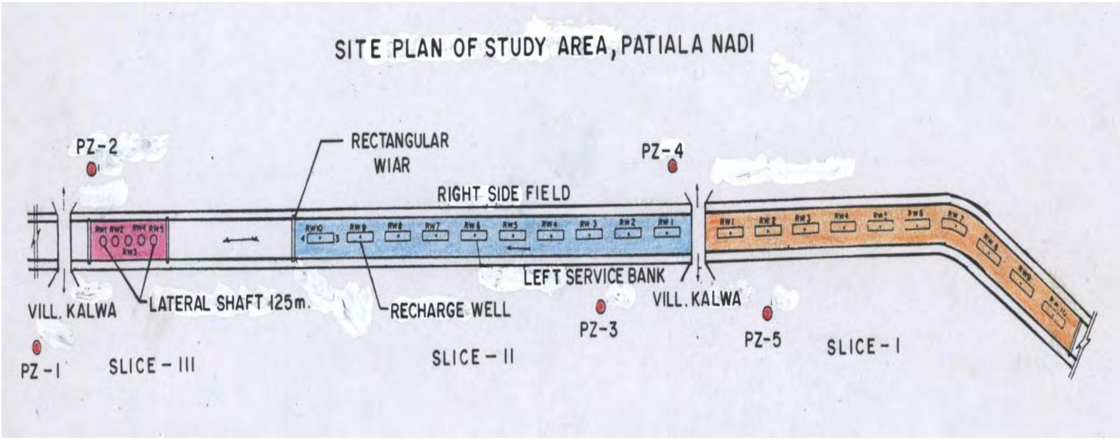

Fig-4. Site plan of study area, Patiala Nadi, District Patiala

Artificial recharge to ground water at Village Channian, district Jalandhar

Artificial recharge scheme was undertaken by utilizing surplus canal water and pond water in the village Channian. The stage of ground water development of Nakodar block of Jalandhar district is 213% as on 31.3.2004. The scheme consists of one recharge well of 81 meter depth and two piezometers of 73 and 34 meter depth , modifying abandoned dug well with recharge well of 33.5 meter and a shaft of 3 meter dia. with recharge well for recharging pond water. The structures were designed to utilize 2,88,924 m^3/year canal water and 16,000 m^3 pond water for recharge. During recharge impact assessment from March 2000 to October 2002 about 8,47,700 m^3 canal water was recharged through recharge well and dug well cum recharge well. It is also estimated that 47,385 m^3 rainwater and village waste water from pond was recharged through shaft cum recharge well.

Roof Top Rain Water Harvesting at Basic Medical Sciences Block, Punjab University, Chandigarh.

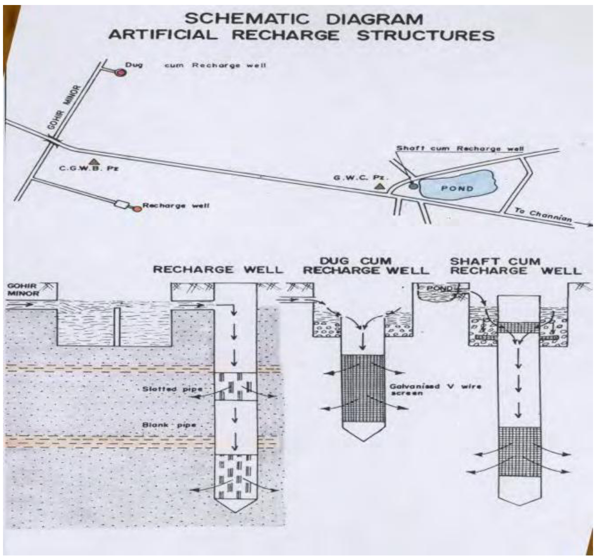

Fig-5.Schematic Diagramme of Artficial Recharge structure

In Chandigarh (UT), the water requirement of the city is met through deep tube wells and by canal water. The city covers an area of 114 km2, out of which 36 km^2 is rural and 78 km^2 is urban. Due to increase in urbanization the paved areas are increasing leading to decrease in unpaved areas for natural recharge. The recharge is mainly through rainfall, which takes place in the recharge areas in the northeastern and eastern parts of the city. Deeper aquifer system sustain majority of the ground water withdrawal resulting into the decline in water levels, which needs replenishment. Due to heavy development of ground water, water levels of deeper aquifers in Chandigarh are continuously declining. The best option for the city is to harvest rooftop rainfall from buildings and paved areas. With this in view, roof top rainwater harvesting for artificial recharge was taken up in the building of Basic Medical Sciences of Punjab University

The Basic Medical Sciences block has roof area of about 2100 m^2. Subsurface geology of the area shows that at the top sand clay layer of 3m exists overlying the shallow unconfined aquifer extending down to about 14m. Below 14m the aquifer zones exist alternating with thick clay zones down to depth of 73m. Water bearing zones are comprised of fine to medium sand mixed with gravel and pebble. The thickness of clay beds varies from 3m to 17m and aquifer zones are 1.53 m to 12.50 m in thickness.

The rooftop rainwater harvesting structure consists of mainly three components, namely, rainwater conveyance system, collection and filtration chamber and a recharge well. The conveyance system to collect and transport rainwater from the rooftop to the collection chamber was already available and laid out up to the corner of the play ground. A trench of 10 m length, 1.7m width and 2.5m depth was constructed in the corner of the play ground near Basic Medical Sciences block and filled with inverted filter. Recharge well 66 m depth was constructed by tapping aquifer zones from 45-51m and 57.50 to 63.50 m depth. Considering spillage, evaporation, leakage and other wastage as 10% ,the remaining 90% of rainfall that falls on the roof top is considered as effective runoff from the roof top. The total rainfall received during the study period was 1201 mm, resulting in 2135m^3 of roof top surface runoff. Out of this, 1985m^3 of water is estimated to be recharged to the ground water reservoir, which is 93% of roof top runoff generated.

Acknowledgement

The author gratefully acknowledges various studies pertaining to artificial recharge carried out by his colleagues from Central Ground Water Board in the state of Punjab, data from which has been extensively used in this paper. The author is thankful to Sri B. M. Jha, Ex-Chairman, and Dr S. C. Dhiman, Chairman, Central Ground Water Board for their encouragement and guidance in writing of this paper.

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Ground Water Vulnerability Assessment – Challenges and Opportunities

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Abstract

Pollution of groundwater due to industrial and municipal wastes is of rising concern in many cities and industrial clusters in India. Though groundwater is not easily contaminated yet once this occurs it is difficult to remediate. The replacement cost of a failing local aquifer is generally high and its loss may stress other water resources looked to as substitutes. Further, in the developing world, such remediation may prove practically impossible. Thus it is important to identify which aquifer systems and settings are most vulnerable to degradation. This can be achieved through several aquifer vulnerability assessment methods. These methods are primarily based on process models and statistical or overlay/index methods. Scanning of literature revealed limited application of such groundwater vulnerability assessment approaches under Indian conditions. Present manuscript attempts to illustrate the strengths and weaknesses of the existing groundwater vulnerability assessment approaches and the consequent opportunities and challenges associated with their wide scale application under Indian conditions.

Introduction

Groundwater is a globally important and valuable renewable resource for human life and economic development. It constitutes a major portion of the earth's water circulatory system known as hydrologic cycle and occurs in permeable geologic formations known as aquifers i.e. formations having structure that can store and transmit water at rates fast enough to supply reasonable amounts to wells. Its importance stems from its ability to act as a large reservoir of water that provides "buffer storage" during periods of drought.

Last 50 years have seen unprecedented development of groundwater resource. At a regional level groundwater is of huge importance in Africa, Asia and Central and South America. Nationally, countries from Palestine to Denmark are dependant on groundwater and examples of local reliance can be drawn from Mexico City to small villages in Ethiopia. An estimated 2 billion people worldwide rely on aquifers for their drinking water supply (Morris *et al*.., 2003).

In rural context, groundwater provides the mainstay for agricultural irrigation and will be the key to providing additional resources for food security. In urban centers groundwater supplies are important as a source of relatively low cost and generally high quality municipal and private domestic water supply. The annual utilizable groundwater resource of India is estimated as 396 km^3 per year. This accounts for about 80% of domestic water requirement and more than 45% of the total irrigation requirement of the country.

Major Groundwater Threats

Groundwater systems are dynamic and water is continuously in slow motion down gradient from areas of recharge to areas of discharge. In large aquifer systems, tens or even hundreds of years may elapse in the passage of water through this subterranean part of the hydrologic cycle. Such flow rates do not normally exceed a few meters per day and compare with rates of up to 1 meter per second for river flow. Velocities can be much higher where flow is through fracture systems, dependent on factors like aperture or fracture network density. In limestones with well-developed solution or in some volcanic aquifers with extensive lava tubes or cooling cracks, velocities can be measured in km/day. Thus supplies located in different aquifers, or in different parts of the same aquifer, can tap water of widely different residence time. This is an important factor for contaminants that degrade over time and in the control of disease-causing micro-organisms such as some bacteria, viruses and protozoa (Morris *et al.*, 2003).

Despite its importance, groundwater is often misused, usually poorly understood and rarely well managed. The main threats to groundwater sustainability arise from the steady increase in demand for water (e.g., rising population and per capita use, increasing need for irrigation, etc) and increased use and disposal of chemicals to the land surface. For instance, in India about 40% of land area is irrigated through large canal water distribution systems. Between 1950 and 2001, the irrigated area in India increased from about 23 Mha to over 80 Mha (Chowdary *et al.*, 2005). In the same period, consumption of inorganic fertilizers also rose from less than a million tons to over 18 million tons. A large scale expansion of irrigated agriculture and a rapid growth in the use of chemical fertilizers in India during 1950s–1980s though contributed significantly to the green revolution and increased food security in the region, as evident from an increased food production from 50 million tons in 1950 to about 210 million tons in 2001, yet it also resulted into large scale degradation of soil and groundwater quality due to extensive seepage and percolation losses from canal network and agricultural fields particularly with rice cultivation (Ozha *et al.*, 1993; Vijay Kumar *et al.*, 1993).

Pollution of groundwater due to industrial effluents and municipal wastes in water bodies is another major concern in many cities and industrial clusters in India. Disposal of treated and untreated industrial effluents on the land has become a regular practice in many countries. A 1995 survey undertaken by Central Pollution Control Board identified 22 sites in 16 states of India having ground waters degraded with industrial effluents. Shallow aquifers in the Ludhiana city have also been reported to be polluted by a stream which receives effluents from 1300 industries. Industries located in Mettupalayam taluk, Tamil Nadu (Sacchidananda and Prakash, 2006) are an excellent example of this practice. A study attempting to capture the environmental and socio-economic impacts of industrial effluent irrigation around different industrial locations in Mettupalayam taluk showed that continuous disposal of industrial effluents on the adjacent farm lands resulted in both groundwater pollution and increased soil salinization. In some locations even drinking water wells (i.e. deep bore wells) were degraded. It was observed that this greatly impacted the revenue from the banana cultivation in the area.

Disposal of solid wastes on land surfaces could be the other source of ground water contamination. Intensive use of chemical fertilizers in farms and indiscriminate disposal of human and animal waste on land result in leaching of the residual nitrate causing high nitrate concentrations in groundwater. It has been reported that nitrate concentrations in parts of 95 districts of 11 states and two blocks of NCT-Delhi are beyond permissible limit of 45 ppm. Mor *et al.* (2005) studied the impact of leachate percolation from Gazipur landfill site on the adjacent groundwater quality. Concentrations of various physico-chemical parameters including heavy metals (viz., Cd, Cr, Cu, Fe, Ni, Pb and Zn) and microbiological parameters (total coliform and fecal coliform) were determined in both groundwater and leachate samples. The effect of depth and distance of the well from the pollution source was also investigated.

Modern agriculture practices reveal an increased use of pesticides and fertilizers to meet increasing food demand for rising population. Non-point pollution caused by fertilizers and pesticides used in agriculture, often dispersed over large areas, is a great threat to fresh groundwater ecosystems. Many of the pesticides and herbicides are cumulative poisons. A study conducted by Tariq *et al.* (2003) in Pakistan, evaluated pesticide contamination of ground water in four intensively cotton growing districts. Water samples were collected from 37 rural open wells in the Bahwalnagar, Muzafargarh, D.G Khan and Rajanpur districts of Punjab district and were analyzed for eight most commonly used pesticides. Information on the distance to the nearest pesticide mixing / application areas was also obtained for each site. From the eight pesticides analyzed, six pesticides were detected in the water samples. The study emphasized the need for monitoring pesticide contamination in rural water resources and developing a drinking water quality standard for specific pesticides in Pakistan.

Nalini *et al.* (2004) also conducted a similar study to investigate concentrations of both organo-chlorine and organ phosphorus pesticides in the surface and ground water samples of Kanpur district in northern

India. In the ground water samples collected from the various hand pumps located in the agricultural and industrial areas, both γ-HCH (0.900 μg/l) and malathion (29.835 μg/l) and dieldrin (16.227 μg/l) were detected. Pesticide like DDE, DDT, aldrin, ethion, methyl parathion and endosulfan were not detected in the surface and groundwater samples. Jayasree and Vasudevan (2006) also undertook a study to know the levels of organo-chlorines in the groundwaters of Thiruvallur district in Tamil Nadu. It was observed that these groundwaters were highly contaminated with pp-DDT (14.3 μg/l), op-DDT (0.8 μg/l), endosulfan, HCH and their derivatives. Among the HCH and endosulphan derivatives, γ-HCH residues (9.8μg/l) were found to be highest in Arumbakkam open wells while the endosulfan sulfates (15.9 μg/l) were highest in the bore wells of Kandigai village. In fact DDT, BHC, carbamate, Endosulfan, etc., which are the most common pesticides used in India, have been widely reported in the ground waters (Kumar and Shah @ www.indiawaterportal.org).

The incidence of high concentrations of arsenic in drinking water has also emerged as a major public-health problem. Arsenic concentrations, above permissible levels of 50 ppb, have been reported in the alluvial plains of Ganges covering six districts of West Bengal. With newer-affected sites discovered during the last decade, a significant change has been observed in the global scenario of arsenic contamination, especially in Asian countries. A study conducted by Mukherjee *et al.* (2006) presents an overview of the current scenario of arsenic contamination in countries across the globe with an emphasis on Asia. Along with the present situation in severely affected countries in Asia such as, Bangladesh, India, and China recent instances from Pakistan, Myanmar, Afghanistan, Cambodia, etc. have also been elaborated.

Increasing incidence of fluoride concentrations (above permissible levels of 1.5ppm) have also been reported for 69 districts in 14 Indian states (e.g. Andhra Pradesh, Bihar, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal). It is estimated that about 65 % of Indian villages are exposed to fluoride risk (Kumar and Shah @ www.indiawaterportal.org). All these areas excepting West Bengal were also reported to be associated with high levels of salinity risks.

Other heavy metals have also been reported to be present in the ground waters of 40 districts in 13 Indian states (e.g. Andhra Pradesh, Assam, Bihar, Haryana, Himachal Pradesh, Karnataka, Madhya Pradesh, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh, and West Bengal) and several blocks of NCT-Delhi (Kaur and Rani, 2006) and Gurgaon and Mewat districts (**Kaur et al.,2008**). However, globally the biggest challenge to groundwater quality is not from high-profile contaminants like arsenic or toxic industrial chemicals but salinization.

Need of Groundwater Vulnerability Assessments

Despite threats from potentially polluting activities, groundwater is often surprisingly resilient and water quality over large areas of the world generally remains good. In part this is because many aquifer systems possess a natural capacity to attenuate and thereby mitigate the effects of pollution. Though groundwater is not easily contaminated yet once this occurs it is difficult to remediate. The replacement cost of a failing local aquifer is generally high and its loss may stress other water resources looked to as substitutes. Further, in the developing world, such remediation may prove practically impossible. Thus it is important to identify which aquifer systems and settings are most vulnerable to degradation.

The vulnerability studies enable assessment of how severe the likely consequences of pollutant loading may be. The severity of the consequences is measured in terms of water quality deterioration. Lobo-Ferreira and Cabral (1991) proposed that groundwater vulnerability to pollution be defined, in agreement with the conclusions and recommendations of the International Conference on Vulnerability of Soil and Groundwater to Pollutants (Duijvenbooden and Waegeningh 1987), as the sensitivity of groundwater quality to an imposed contaminant load, which is determined by the intrinsic characteristics of the aquifer. Thus defined vulnerability is distinct from pollution risk, which depends not only on vulnerability but also on the existence of significant pollutant loading entering the subsurface environment. It is possible to have high aquifer vulnerability but no risk of pollution, if there is no significant pollutant loading or to have high pollution risk in spite of low vulnerability, if the pollutant loading is exceptional. It is important to clarify the distinction between vulnerability and risk. This is because risk of pollution is determined not only by the intrinsic characteristics of the aquifer, which are relatively static and hardly changeable, but also on the existence of potentially polluting activities, which are dynamic factors that can, in principle, be changed and controlled. The seriousness of the impact on water use will depend not only on aquifer vulnerability to pollution but also on the magnitude of the pollution episode, and on the value of the groundwater resource.

Groundwater Vulnerability Assessment Techniques

Many approaches have been developed to evaluate aquifer vulnerability. These include process based methods, statistical methods, and overlay / index methods (Zhang *et al.*, 1996; Tesoriero *et al.*, 1998). The process based methods use simulation models to estimate the contaminant migration (Barbash and Resek, 1996). Statistical methods use statistics to determine associations between the spatial variables and the actual occurrence of pollutants in the groundwater. While the overlay / index methods use location specific vulnerability indices based on the factors controlling movement of pollutants from the ground surface to the saturated zone. Of these major approaches, the overlay/index method has been the most widely adopted approach for large scale aquifer sensitivity and ground water vulnerability assessments.

Overlay/ Index Models

The overlay/ index models are based on combining maps of various physiographic attributes by assigning an index or score to each attribute (NRC, 1993). Qualitative or quantitative indices are derived, that bring together the key factors believed to determine pollutant transport processes (Connell and van den Daele, 2003). Thus overlay/ index-based ground water vulnerability mapping models essentially integrate ratings and attributes of important factors (viz., contaminant properties, depth-to-water table, recharge rates, soil / aquifer properties, land use and management practices) controlling pollutant transport from a ground surface to an aquifer (Hamerlinck and Ameson, 1998). Early examples of this type of assessment are the DRASTIC index (Aller *et al.*, 1985) and the GOD index (Foster, 1987). A number of similar index-based systems have been developed, sometimes extending the range of parameters included in the vulnerability assessment (Secunda *et al.*, 1998). Vulnerability maps based on these methods have proved popular tools and are a common feature of groundwater quality management throughout the world, as documented by Worrall and Kolpin (2004). The main advantage of such approaches is that some of the factors such as rainfall and depth to groundwater are easily available over large areas thereby enabling regional scale assessments (Thapinta and Hudak, 2003).

Nitrate nitrogen (NO_3^-N) contamination of aquifers is an important global problem. Ceplecha *et al.* (2004) designed two tools to assess aquifer vulnerability to NO_3^-N contamination in Colorado. The first tool enables statewide aquifer vulnerability mapping (VM) for identifying regions vulnerable to ground water contamination. The VM approach uses five factors viz., aquifer location, groundwater depth, soil drainage class, land use, and recharge availability for assessing aquifer vulnerability on a regional scale. Validation of VM on 576 discrete ground water sample points across the study area showed that it could successfully ($r^2 = 0.78$) delineate aquifers with increased NO_3^-N vulnerability. The second aquifer assessment tool enables field scale vulnerability matrix (VMX) development and thereby helps practitioners determine relative field-scale aquifer vulnerability to NO_3^-N contamination and suggest any changes required in the management practices for reducing groundwater vulnerability. The VMX consists of a series of factors that are rated and combined for a particular field. The VMX can even be used in conjunction with the VM tool to determine NO_3^-N contamination potential from intensive agriculture.

The overlay/ index-based sensitivity and vulnerability mapping approaches have evolved considerably since their inception in the early 1980s, particularly with regard to the use of parameter weighting schemes and the utilization of GIS technology (Corwin *et al.*, 1997; Fuest *et al.*, 1998). An excellent example of this is the DRASTIC program of Aller *et al.* (1985). This program was originally developed for manual overlaying of semi-quantitative data layers (such as depth to water table, net recharge, aquifer media, soil media, topography and hydraulic conductivity) and thereby ranking regions with respect to their groundwater vulnerability to pesticides. This entire analysis has been recently shown to be feasible through the use of the GIS technology as well (Fabbri and Napolitano, 1995). Though DRASTIC has been successfully validated for the occurrence of a specific pollutants such as pesticides and nitrates in the groundwater system (Navulur and Engel, 1998). Yet it has been shown to be a poor predictor of general groundwater vulnerable regions (Maas *et al.*, 1995; Barbash and Resek, 1996; Garrett *et al.*, 1989; Koterba *et al.*, 1993; USEPA, 1993).

Secunda *et al.* (1998) used composite models along with DRASTIC for the assessment of groundwater vulnerability in Israel. The methodology employed extensive agriculture land use data and empirical means to characterize aquifer vulnerability. Al-Adamat *et al.* (2003) also produced groundwater vulnerability and risk maps for Azraq basin of Jordan using GIS, remote sensing and DRASTIC. These maps were designed to show areas with greatest potential for groundwater contamination on the basis of their hydro-geological conditions and human impacts.

Lowe *et al.* (2003) applied a similar overlay/ index approach on the existing data for western United States to produce pesticide sensitivity and vulnerability maps using GIS methods. Hydro-geologic setting (vertical ground-water gradient and presence or absence of confining layers), soil hydraulic conductivity, retardation of pesticides, attenuation of pesticides, and depth to ground water were the main factors used for determining ground-water sensitivity to pesticides. The study revealed that the irrigated lands with ground-water table closer to the land surface had higher potential for water quality degradation due to surface application of pesticides.

Babiker *et al.* (2004) also used a GIS integrated DRASTIC model to evaluate vulnerability of Kakamigahara aquifer in Central Japan. It was observed that net recharge has the largest impact on the intrinsic vulnerability of the aquifer. This was followed by the soil media, topography, vadose zone media and hydraulic conductivity. The integrated vulnerability map revealed high risk on the intensively vegetable cultivated (eastern) part of the Kakamigahara aquifer. Dixon (2005) also developed similar ground water vulnerability maps through the use of three newly developed indices based on the detailed land use, pesticide and soil structure information and the selected parameters from the DRASTIC model. GIS, GPS, remote sensing and fuzzy rule-based methods were used for generating groundwater sensitivity maps. It was observed that these three indices could compare well with the modified DRASTIC Index (DI, Al-Adamat *et al.*, 2003) and the field water quality data.

Groundwater vulnerability and risk mapping assessment based on a source–pathway–receptor approach was also presented by Nobre *et al.* (2007) for an urban coastal aquifer in northeastern Brazil. A modified version of the DRASTIC methodology was used to map the intrinsic and specific groundwater vulnerability. The integration of fuzzy hierarchy methodology and numerical modeling provided the mechanism to assess groundwater pollution risks and identified areas with potential threats that must be prioritized in terms of groundwater monitoring and restriction on use. A groundwater quality index based on nitrate and chloride concentrations was also calculated.

A number of other alternative index methods based on a range of parameters such as land-use (Crowe and Booty, 1995), travel time (Maxe and Johansson, 1998), chronic toxicity (Britt *et al.*, 1992) and attenuation and retardation factors (Rao *et al.*, 1985; Kookana and Aylmore, 1994; Wooff *et al.*, 1999) have been developed. For example, Shukla *et al.* (2000) applied an attenuation factor based method of Rao *et al.* (1985) to show that there was a general agreement between the vulnerability prediction and observed groundwater contamination. Zektser *et al.* (2004) used a Point Count System (PCS) to study the impact of pollution on Snake River aquifer system in eastern Idaho, United States. In this approach also the influence of each factor (e.g. depth to water, conduct properties of unsaturated medium and recharge) was ranked as per the expert assessment and the groundwater vulnerability was characterized by rank sum.

Stewart *et al.* (2004) applied a Type Transfer Function (TTF) approach to generate a regional-scale non point-source ground water vulnerability assessment for the San Joaquin Valley, California. The comparatively computationally inexpensive TTF approach could produce quantitative estimates of contaminant concentrations for large regional scales through characteristic functions based on different soil textures and their leaching properties. The TTF simulations employed an extensive soil and recharge database to estimate atrazine (1-chloro-3-ethylamino-5-isopropylamino-2, 4, 6-triazine) concentrations at a compliance depth of 3 m resulting from a surface application. Two different sets of TTFs with two different levels of up- scaling were used for spatially uniform and distributed recharge estimates. Results showed that estimated atrazine concentrations can be related to soil survey information. Sandy loam and loamy soils with low organic carbon contents were found to be associated with high vulnerability to atrazine leaching. Travel times for atrazine peak concentrations to the compliance depth ranged from 350 to 730 days. The extent of areas with estimated atrazine concentrations above the maximum contaminant level was less extensive when uniform annual recharge values were used. Simulated TTF concentrations were highest for eastern Fresno County. The TTF modeling approach was shown to be a useful tool for quantitative pesticide leaching estimates at regional scales. The so simulated vulnerability pattern was also supported by field observations.

Simplified pollutant transport models have also been used (Meeks and Dean, 1990) for assigning weights and ranks to the principal (indicator) variables. The development and application of a GIS based decision support framework that integrates field scale models for assessment of non-point-source pollution of groundwater in canal irrigation project areas was presented by Chowdary *et al.* (2005). The development and application of this framework was illustrated by taking a case study of a large canal irrigation system in India. Alternate strategies for water and fertilizer use could be evaluated using this framework to ensure long-term sustainability of productive agriculture in large irrigation projects.

However, the overlay/ index methods suffer from several flaws (Foster, 2002) thereby limiting their scope as only relative indices of aquifer sensitivity. One of the primary flaws in this approach is the arbitrary selection of parameter weights, based on some expert opinion (Fobe and Goossens, 1990). Worrall *et al.* (2005) calculated the vulnerability of groundwater to pesticide contamination based on a Bayesian method for the major aquifer units of southern England. The method was applied to the actually monitored data and hence did not rely on any expert opinions or pollutant transport models. The technique combined information from different sets of observations over periods of years and for a range of pesticide compounds and provided a measure of vulnerability on a continuous probabilistic scale (0 - 1). The resulting vulnerability map could show local and regional scales variations, both within and between major aquifer units. However, Troiano *et al.* (1997) in his overlay/ index approach assumed similar mobility rates for different pesticides for identifying regions vulnerable to pesticide contamination across several wells in California. Hence, unlike statistical approaches, the overlay/ index methods in general can not differentiate between contaminants and hence are applicable to the assessment of the intrinsic vulnerability only (Connell and van den Daele, 2003).

Some indices such as the UK ground water vulnerability index (Palmer *et al.*, 1995) neither incorporate any aquifer properties nor account for any relative importance of the factors (in terms of their relative weights). Besides this, the UK system neither includes climatic factors nor depth to the water table (Palmer *et al.*, 1995). Worral and Kolpin(2004) examined the validity of the UK vulnerability system (Palmer and Lewis, 1998) and found it to be in complete statistical disagreement with the actual groundwater contamination observations.

Besides this, the overlay/ index-based vulnerability systems are not probabilistic and hence have limited decision making capabilities (Merchant, 1994). Further most of these approaches have not been widely validated. Schlosser *et al.* (2002) developed a similar pesticide vulnerability index and showed a good agreement with the actual groundwater observations. However these observations were not supported with any statistical test of validation.

Process Based Simulation Models

Assessment methods in this category are usually more elaborated than simple overlay or index methods, and include different degrees of complexity from process-based indices to complex 3-D simulation models.

Simple models such as the Behavior Assessment Model (BAM; Jury and Ghodrati, 1989) or the Attenuation Factor (AF; Rao *et al.*, 1985) can be used to map groundwater vulnerability, but they can also serve for screening purposes (i.e. to compare the environmental fate of a new compound with other pesticides). The AF is an analytical solution of the convection-dispersion equations. Indices can also be based on numerical solutions of the transport equations. For example, Meeks and Dean (1990) used a one-dimensional advection-dispersion transport model to develop a leaching potential index, which simulates vertical movement through a soil to the water table. Soutter and Pannatier (1996) expressed groundwater vulnerability as the ratio between the cumulative pesticide flux reaching mean water table depth and the total quantity of pesticide applied. The derivation of such indices is not necessarily a common feature of vulnerability assessments using process-based models. The selection of a single relevant variable can serve the purpose of estimating groundwater vulnerability. For example, Connell and van den Daele (2003) chose the maximum contaminant concentration at the water table as a proxy for groundwater vulnerability.

Vulnerability assessments can also be based on meta-models. A meta-model is basically a 'model of a model'. It is a statistical significant response function that approximates outcomes of a complex simulation model (Wu and Babcock, 1999; Pineros Garcet *et al.*, 2006). In environmental sciences, meta-models are usually based on multiple regression analyses, artificial neural networks, transfer functions, multidimensional kriging, etc. For example, Tiktak *et al.* (2006) mapped groundwater vulnerability at the pan-European scale using a combination of AF and a meta-model of GeoPEARL.

Statistical Inference Models

Statistical methods use response variables such as the frequency of contaminant occurrence, contaminant concentration, or contamination probability. These methods are based on the concept of uncertainty, which is described in terms of probability distributions for the variable of interest (NRC, 1993). One possible goal in applying statistical methods to vulnerability assessment is to identify variables that can be used to define the probability of groundwater contamination (Burkart *et al.*, 1999a). Typically, one seeks to describe in mathematical terms (function or model) a relation ship between water quality and natural and/or human-induced variables in a discrete area.

For example, Teso *et al.*, (1996) developed a logistic regression model containing independent variables related to the soil texture. The dependant variable was defined as the contamination status of soil sections (uncontaminated vs. contaminated) and groundwater vulnerability was thus assessed through the estimation of a section's likelihood of its containing a contaminated well. Other statistical approaches, such as principal components analysis, discriminant analysis and cluster analysis, have been used to describe relationships between soil attributes and groundwater vulnerability (e.g. Teso *et al.*, 1988; Troiano *et al.*, 1997).

Worrall (2002) and Worrall and Kolpin (2003) used Bayesian statistics to measure the vulnerability of the catchment of a borehole to groundwater pollution, based on observation of contaminant occurrence in the borehole and the region. This vulnerability assessment is thus based solely on monitoring data and does not need explanatory variables. However, the application of this method requires extensive data sets (and hence is limited to large, intensively monitored areas) and appears to be less sensitive for boreholes with a low relative vulnerability (Worrall, 2002). Moreover, for regulation purposes, this approach implies that borehole catchments can actually be delineated.

Worrall and Kolpin (2004) developed a logistic regression model of ground water pollution that brings together variation in chemical properties with land-use, soil and aquifer properties. They found that vulnerability, as explained by the independent factors that produced the best regression fit, could be viewed as having two parts: an intrinsic vulnerability factor (consisting of variables related to the depth to groundwater, the organic matter and the sand content) and a molecular factor (consisting of variables related to molecular connectivity). However, the regression output is limited to the presence/absence of a compound, and hence limits the discrimination to vulnerable vs. invulnerable wells. Although the mapping of such a vulnerability assessment might prove to be problematic, this study is an excellent example of a statistical vulnerability assessment which explicitly accounts for the variability of both chemical and site properties.

Conclusions

Although, in contrast to the other process / statistical inference based models, the overlay/ index models are less constrained by data shortage and computational difficulties (Barbash and Resek, 1996) yet they have a number of conceptual flaws. Firstly, weightings are chosen arbitrarily and solely based on expert opinion (NRC, 1993; Worrall, 2002; Connell and van den Daele, 2003). Secondly, systems based on indices do not capture the probabilistic nature or the uncertainty of groundwater vulnerability (Worrall, 2002). Thirdly, uncertainties in the data themselves and in the actual relevance of each weighted factor question the reliability of the vulnerability maps (Merchant, 1994). Fourthly, the use of indices makes validation difficult. Merchant (1994) noticed that, apart from the use of 'visual validation', very few attempts have been made to validate the numerous DRASTIC applications. Worrall (2002) stressed that validation may be inherently impossible for this category of methods that assess vulnerability outside of a probabilistic framework. Finally, these methods have a greater focus on the distribution of environmental attributes rather than on processes directly controlling groundwater contamination by pesticides (Connell and van den Daele, 2003). These numerous limitations suggest that overlay and index methods will receive decreasing support in the future. However there are reports that suggest that overlay/ index methods could still be useful in combination with the process-based models (Gogu and Dassargues, 2000). Kaur et al. (Manuscript in preparation) successfully applied a similar methodology, based on an indigenously developed pre-validated (process-based) field scale decision support system named IMPASSE (Kaur, 2004), to assess salt and trace metal vulnerability of local ground-waters to the on-going agricultural practices in the peri-urban agricultural lands of the Faridabad block. A comparison of these salt and trace metal vulnerabilities with the actually observed ground water quality data for each test site confirmed that the presence of salts in the study area ground waters was geogenic and that on-going agricultural practices were not responsible for it.

Hence it is very evident that such regional aquifer vulnerability assessments, if properly conducted, can enable informed management decisions so as to afford early warning of degradation and devise an effective strategy for sustainable ground water management. This can ultimately increase the chances of closing the gap between policy enactment and enforcement – so often a stumbling block to achieving sustainable water use.

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Hydromorphogeological Microzonation to Infer Groundwater Potential and Quality in National Capital Region

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Abstract

Multi-sensor satellite data integrated with Global Positioning System enabled geophysical and geochemical information has the potential to infer the availability and quality of groundwater in metamorphic Aravali formation of National Capital Region. Surface manifestation of satellite data has the potential to infer subsurface geology as well as soil moisture in weathered aquifer material. Normalized Difference Vegetation Index computed from the vegetation above the inferred lineament has the potential to infer groundwater quality. Electrical resistivity, X-Ray diffraction (XRD) and Induced Couple Plasma Emission Spectrophotometer (ICPES) analysis further support the spectral reflectance anomaly in litho units. Deep seated fractures with interconnected morphological manifestation have been inferred by using Proton Precession Magnetometer anomaly data. Although it was not possible to infer very deep seated potential fractures by using satellite data but the accurate ground truthing by geophysical investigations has been used to provide a clear hydromorphogeological attribute of potential aquifers. Drilling litho logs supported by thin section petrography suggests that high grade metamorphism is suggestive of good fractures in quartzite-schist-granite-pegmatite terrain of Aravali formation of Research and referral Hospital and Jawaharlal Nehru University areas. ICPES and XRD analysis of these metamorphic litho-units, weathered material, soil and groundwater confirms that groundwater quality improves with the grade of metamorphism of the Precambrian formation. Eleven deep tube wells were drilled in this terrain down to 150 meter to 185 meters below ground level (bgl) are showing five to seven sets of potential aquifer zones from 25 meter to 165 meter bgl. In most of the cases the shallow aquifer zone ranging from 25 meter to 32 meter bgl were dried up due to over pumping and improper land use practices. After successful tapping of multiple fracture zones in this unconfined aquifer, the piezometric head has shown a substantial rise. Raised groundwater level has laterally recharged the dried aquifers in the water starved Aravali terrain. NDVI attributes further confirm good health of vegetation, which is suggestive of the quality and quantity of groundwater in this area.

Introduction

The National Capital Region (N.C.R) falls in the Western zone of the country. It gets an average rainfall of 632mm/year. Moreover, National Capital Territory (NCT) is situated on the banks of Yamuna which is a tributary of Ganges. Yamuna's water has been channelized to other areas. By the time Yamuna reaches Delhi, it does not remain a river but turns into a drain. The water problem in National Capital Territory is well known. Unprecedented growth of urbanization in the area has resulted in the destruction of the traditional surface water structures for constructing buildings. This has resulted in the scarcity of water for various uses. With the rising population of NCR and the declining availability of water due to industrial pollution & destruction of surface tanks and pond, the water scenario of NCR is alarming. Frequent failure of monsoons, increasing demand and over exploitation leads to depletion of groundwater resources in many parts of the country. Groundwater is not only an important component of the hydrological cycle but also an important source of drinking water. Comparative estimation indicates that probably at least two hundred times the volume of annual run off from the world's river is stored as groundwater beneath the land surface(Maning, 1987).Therefore detailed investigation regarding the occurrence and renewal of groundwater has become necessary. Safe use, tactical exploration and management of groundwater resources require good knowledge and proper understanding of the groundwater regime and its control.

Material and Methodology

Survey of India Toposheets

S.No	Toposheet No.	Scale
1	53H/1	1:50,000
2	53H/2	1:50,000
3	53H/3	1:50,000
4	53H/5	1:50,000
5	53H/6	1:50,000
6	53H/7	1:50,000
7	53D/13	1:50,000
8	53D/14	1:50,000
9	53H	1:250,000
10	53D	1:250,000

Multisensor satellite data were georeferenced for interpretation and delineation to infer potential zones for groundwater exploration and assessment of its quality. Based on the anomalous attributes of satellite data, groundwater exploration sites were selected. Interconnected fracture zones in the Quartzites and Pegmatites shows anomalous NDVI values. Resistivity and magnetic surveys were conducted in these places to recommend sites for drilling. NDVI values of satellite data were further correlated to infer the quality of groundwater. Deep rooted vegetation extracts groundwater from the interconnected fractures. ICPAES study of the groundwater in some areas of Pegmatite and quartzite friction zone shows higher concentration of dissolved ions, which was correlated with the higher attribute of near infrared reflectance. The hydromorphogeological information were interpreted in GIS format to infer the microzonation of units showing qualitative and quantitative character of groundwater.

Software Used

(i) Arc/Info GIS Workstation version 9.1
(ii) Arc View GIS 3.1
(iii) Auto CAD Map 2000
(iv) ERDAS Imagine Image Processing Software Version 8.4
(v) Rockworks 6.9.8
(vi) Geoimage
(vii) SPSS 14 for Windows

Pre-Processing of Satellite Images

The LISS- III image was obtained from NRSA for the year 2005.

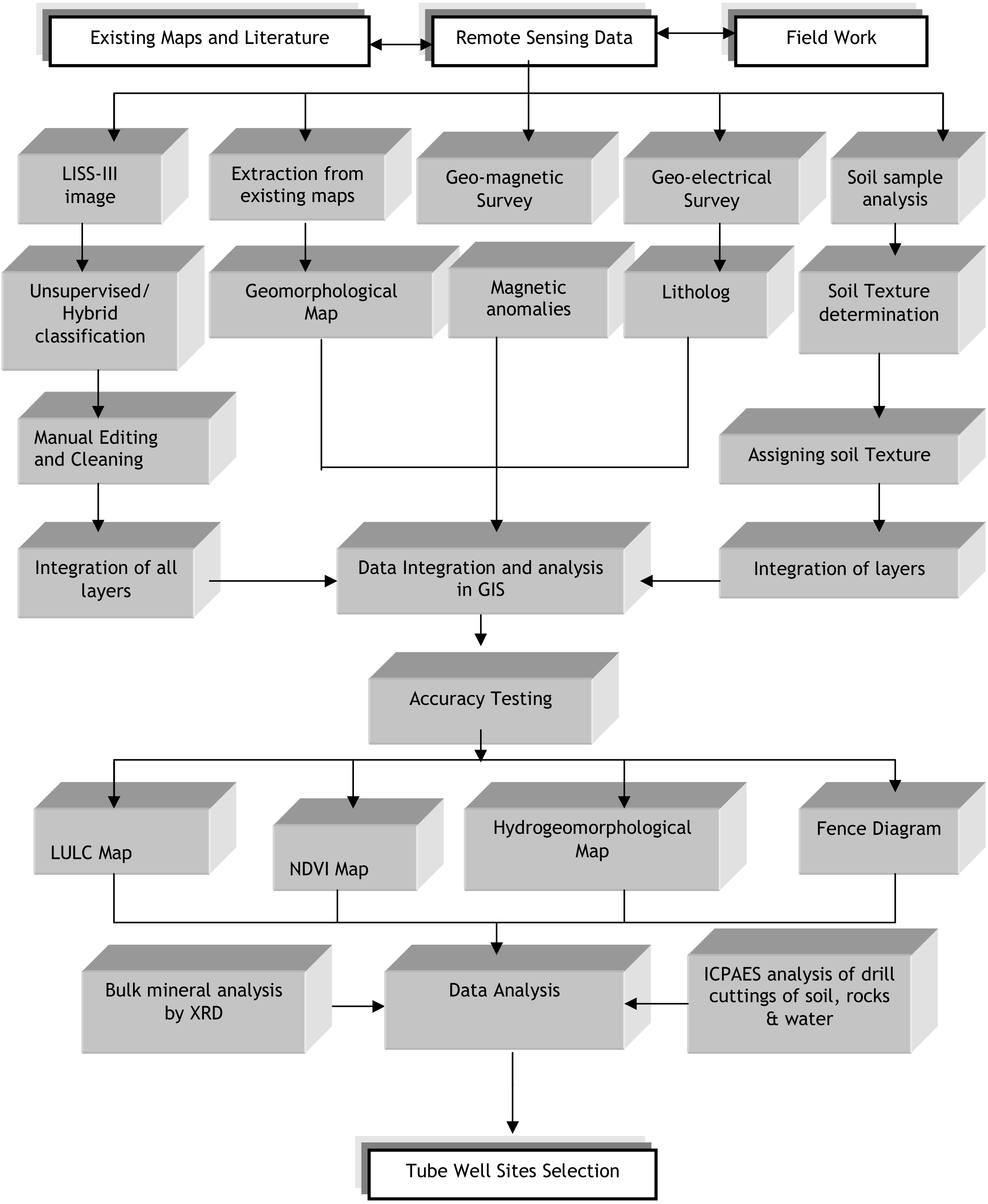
- Satellite image from IRS-1D, LISS-III sensor, on a scale of 1:50,000(geo-coded) representing synoptic view of earth's surface at 25mX25m ground resolution in three spectral bands have been procured. The details of the IRS data used to accomplish the study are given below (Flowchart.1).
- Data product –Standard FCC (False colour composite), bands 1, 2 and 3 in the range of (0.52-0.59 microns) B2, (0.62-0.68microns) B3 and (0.77-0.86microns) B4 respectively.
- Projection: The image was projected to Lambert Conformal Conic Projection, Spheroid and datum Everest.

The SRTM data were processed to transform it into product usable in GIS:-

- Conversion of raw data: the image was converted from the DTED Level-2 format to ESRI grid format (resolution 79.6mX79.6meter).
- Mosaicking: the individual tiles were mosaicked and then was clipped using shape file of study area.
- Projection: The final output of step b was projected into Lambert Conformal Conic projection, spheroid and datum Everest.

The Resourcesat-1 (PAN and LISS III merged) satellite image was projected in the same manner. This ultimately helps in increasing the spatial resolution which helped to determine the lineaments in the area easily.

Flowchart.1 Flowchart showing hydromorphogeological microzonation



Geophysical Investigation

Delhi ridge lineaments were inferred using RESOURSESAT-1 (IRS-P6) Sensor-AWIFS data show a strong trend in NE-SW direction only (Figure.1) Further, the area was studied using IRS-1D Panchromatic and LISS-III sensor data(Figure.2) has shown detailed lineament which passes though Asola Bhati sanctuary, J.N.U. Sports Complex (stadium), RR Hospital and extends up to Bahadurgarh in Haryana (adjacent to north west Delhi). Panchromatic sensor shows detailed land use patterns of Delhi area, which are useful information in water resource management (Figure.3). Measurements were taken along this lineament, which is inferred as sudden decrease in resistivity and magnetic values (average magnetic value of Delhi region is 47,000 gammas). Groundwater recharge map of whole Delhi and specifically ridge area has been prepared by using multisensor satellite data and geophysical investigations. Based on the spot magnetic values in and around NCR region, 20 profiles were done. Contour maps were made along the profile. Contour lines were drawn at every ten gammas interval; Low magnetic values were noticed in lineaments intersections which were showing low resistivity on ferruginous quartzite. Selections of drilling sites

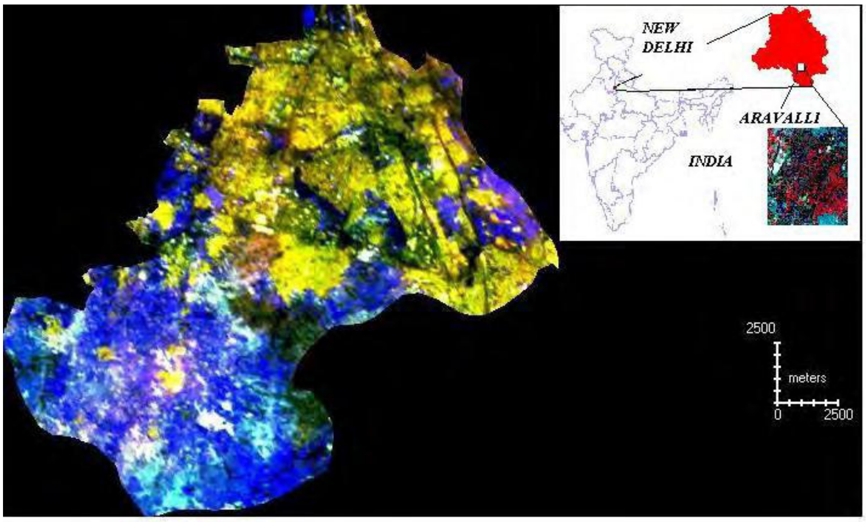


Figure.1AWIFS data of Delhi showing geomorphic microzones

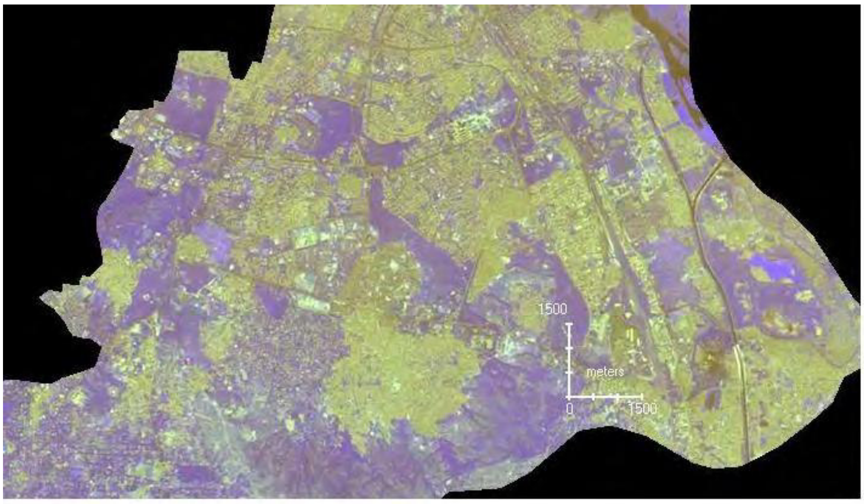


Figure.2.LISS-III sensor showing Hydrgeomorphic microzonation

Figure.3.IRS-1D PAN Data showing Hydrogeomorphic microzonation

were based on the points inferred by magnetometer showing low magnetic values and interconnected lineaments.

X- Ray Diffractometer: - Bulk mineral composition and concentration of the various elements in the drill cuttings were analyzed using the X-Ray diffractometer. Model used is PW 3040/60 X/ Pert PRO Console (Phillips, The Netherlands). Interpretation of modern x-ray diffractograms requires several steps

1. Completely drying the samples
2. The rocks (drill cuts) samples were crushed – 200 mesh in agate pestle and mortar for analysis.
3. Slides are prepared from the meshed samples and put in the X-ray diffractometer to get the x-ray diffractometer in the rd, dat and udf format.
4. The results were then analyzed on X-Pert High Score software.

ICP-AES Analysis: - Multielement Analysis by BRGM Procedure

The geological materials such as rocks, soils and stream sediment samples were crushed – 200 mesh in agate Pestle and mortar for analysis. The geological samples were digested with mixed acid (HF, HCl, HNO3 and $HClO_4$).

<u>Methodology adopted for ICP-AES analysis</u>

Alkaline and acid fluxes are also very effective for the decomposition of refractory minerals. Basic Fluxes efficiently decompose complex silicate and minimize volatilization of minerals. Among these Fluxes, Sodium Hydroxide, Carbonate, Peroxide and their mixtures have been used. Sodium Peroxide is very effective for decomposing materials containing Sn, W, Cr and Mo. The flow sheet scheme for sample treatment, decomposition and dissolution for multi element analysis of rocks, soils and stream sediments by ICP-AES is shown in the figure. BRGM program for the determination of major, minor and trace elements, special wavelengths and limits of detection in solid materials, for geotechnical exploration samples, based on l gm sample in 100 ml (Figure.4).

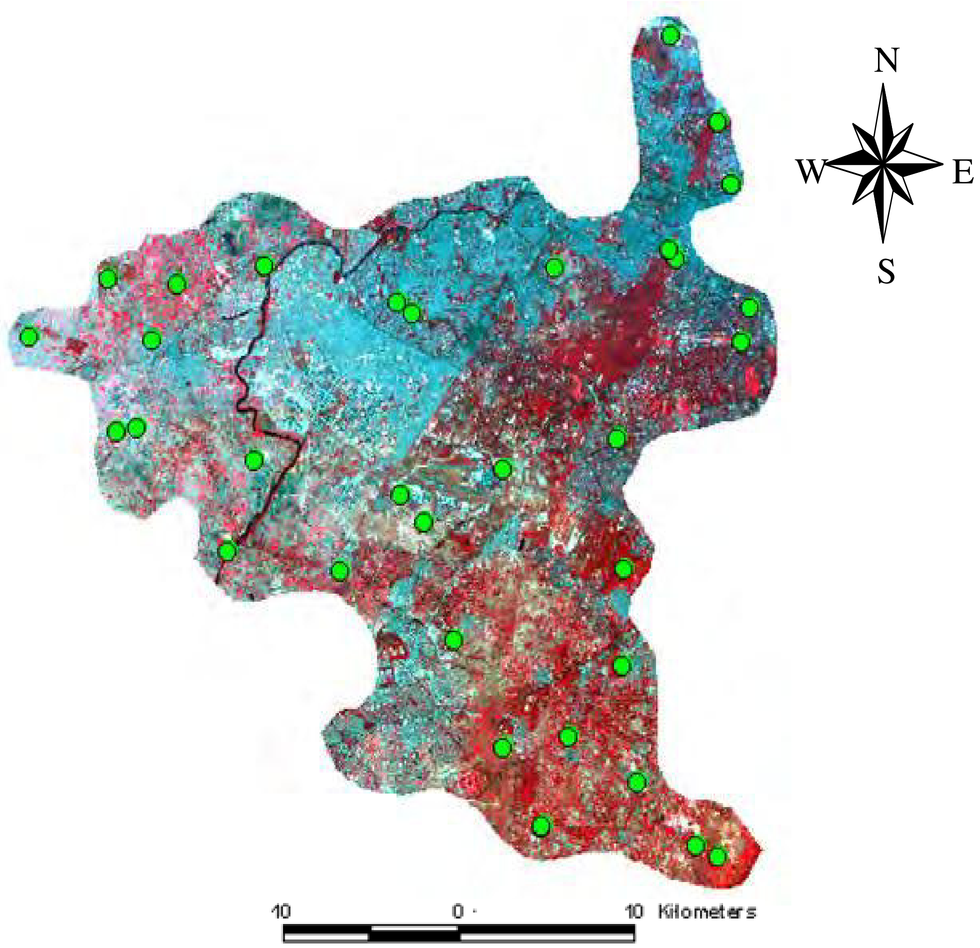


Figure.4.Sampling Sites of the Water Quality data in NCR region

Soil Particle Size Analysis

The particle size analysis of soil estimates the percentage sand, silt and clay contents of the soil and is often reported as percentage by weight of oven dry and organic matter free soil. The analysis is usually performed on air-dry soil. Based on the proportion of different particle sizes, a soil texture category may be assigned to the sample. The first stage in a particle size analysis is the dispersion of the soil into individual particles - sand (>1000μm - <600μm), silt (>600μm - <37μm) and clay (>37μm). The hydrometer method of silt and clay measurement relies on the effects of particle size on differential settling velocities within a water column. Theoretically the particles are assumed to be spherical and have a specific gravity of 2.65. If all other factors are constant, the settling velocity is proportional to the square of the radius of the particle in accordance with stoke's law.

Drilling details

Based on the Remote sensing and Geophysical investigation, exploratory drilling were carried out in 7 locations at JNU and 4 locations in RR Hospital in NCR in 2006-2007. The details of wells drilled in JNU are shown in Table:1.

Table.1.: Drilling site details in part of NCR

Bore	Longitude	Latitude	Easting	Northing	Elevation (in Metres)	Total Depth (in Metres)
JNU 1	77.17186	28.54092	712494.9	3159050	248	182.92
JNU 2	77.17406	28.54642	712698.5	3159663	236	182.92
JNU 3	77.17019	28.54608	712321.4	3159619	250	164.63
JNU 4	77.17078	28.54283	712385	3159260	253	160.06
JNU 5	77.1563	28.5381	710977.6	3158710	263	166.15
JNU 6	77.1619	28.544	711513.9	3159374	250	198.17
JNU 7	77.17251	28.5376	712565.1	3158683	256	146.34

Yield Description

Groundwater occurs in Aravaliis in confined aquifer at various levels in JNU area (24mbgl to 185mbgl). After drilling on scientifically selected suitable sites, 100% success was achieved in this water starved, metamorphic terrain. Based on the lithologs prepared by Remote Sensing Application Laboratory, SES, JNU, slotted pipes were lowered down to scientifically corrected accurate depth zones. The compressor test was carried out. In this process a pipe of diameter inch with orifice diameter of 2.5inch was fitted in the dischrge pipe. Head of the orifice was measured through a transparent rubber tube. Table.2 Shows discharge of groundwater in Lt/hr from circular orifice.

Table .2. Tabulation of dischjrge in Lt/hr from circular orifice

	JNU 1	JNU2	JNU3	JNU4	JNU5	JNU6	JNU7
Head of water in tube above cetre of orifice in (inches)	9	18	25	10	20	9	20
4 inch pipe with 2.5 inch opening in (Lt/hr)	20,475	28,938	34,125	21,840	30,576	20,475	30,576

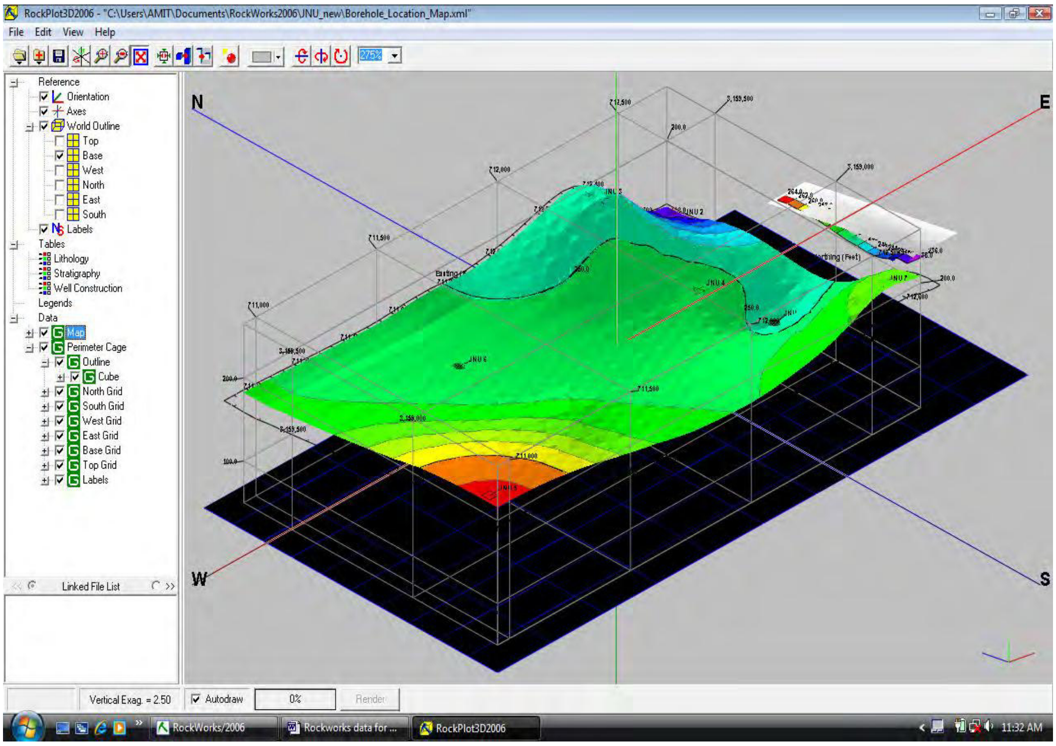


Figure.5.Rockware modelling of elevation contour in NCR area.

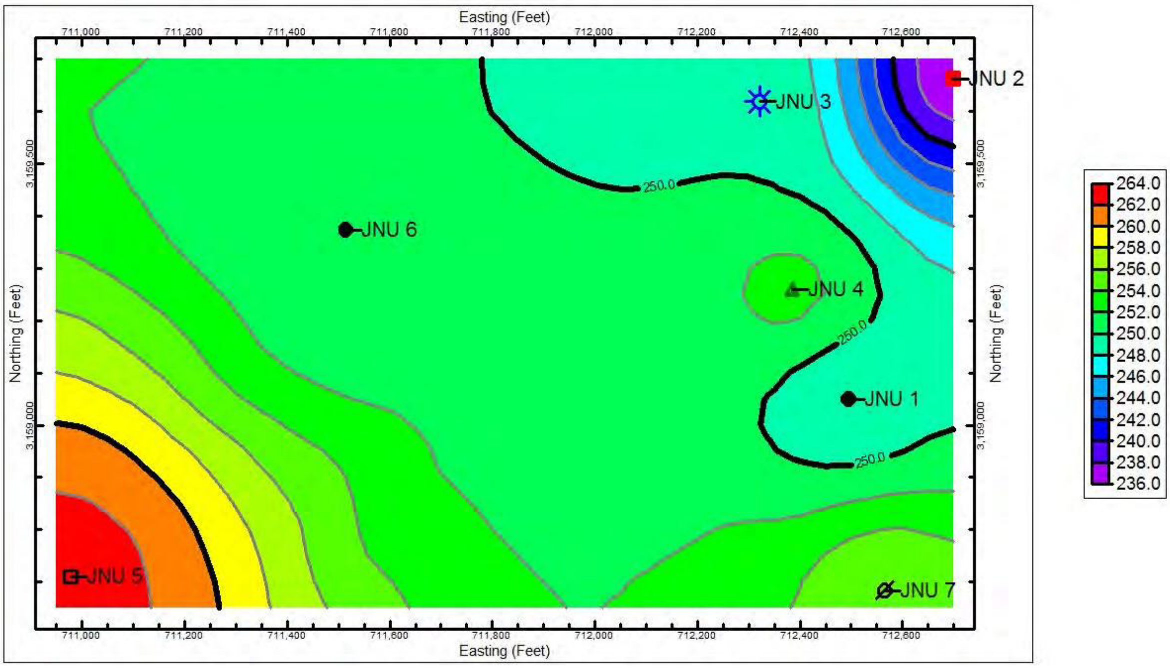


Figure.6.Elevation contours of the sites within study area selected for drilling indicate that elevation naturally increases towards south-west region. Towards eastern and north-eastern parts of study area elevation decreases sharply.

Table.3. Litholog of Drilled wells in a part of NCR (JNU)

Bore	Depth1 (in metres)	Depth2 (in metres)	Lithology
JNU 1	0	9.14	Top soil dry
JNU 1	9.14	18.29	Clay and silt
JNU 1	18.29	32.01	Sand and Clay
JNU 1	32.01	45.73	Clay, Quartzite
JNU 1	45.73	64.02	Weathered Quartzite
JNU 1	64.02	82.31	Weathered Quartzite and Feldspar Veins
JNU 1	82.31	86.89	Quartzite veins and Feldspar veins
JNU 1	86.89	96.03	Weathered Quartzite and Aplite
JNU 1	96.03	105.18	Hard compact quartzite
JNU 1	105.18	114.32	Fractured quartzite
JNU 1	114.32	118.9	Non ferruginous quartzite
JNU 1	118.9	137.19	Fractured quartzite
JNU 1	137.19	150.91	Non ferruginous quartzite
JNU 1	150.91	164.63	Quartz and Feldspar veins
JNU 1	164.63	182.92	Coarse quartzite
JNU 2	0	4.57	Top soil
JNU 2	4.57	9.14	Clay and silt
JNU 2	9.14	13.71	Ferruginous intercalation
JNU 2	13.71	22.86	Sand and ferruginous quartzite
JNU 2	22.86	36.58	Sand , clay and quartzite
JNU 2	36.58	41.58	Ferruginous quartzite and mica
JNU 2	41.58	50.3	Weathered mica schist
JNU 2	50.3	59.45	Weathered mica schist and quartz vein
JNU 2	59.45	73.17	Ferruginous quartzite
JNU 2	73.17	96.03	Fractured quartzite
JNU 2	96.03	100.6	Hard compact quartzite
JNU 2	100.6	105.18	Quartzite and mica schist
JNU 2	105.18	109.75	Ferruginous quartzite
JNU 2	109.75	114.32	Mica schist and quartz vein
JNU 2	114.32	128.04	Ferruginous mica schist and quartz vein
JNU 2	128.04	132.62	Compact mica schist
JNU 2	132.62	137.19	Fractured quartzite
JNU 2	137.19	146.34	Ferruginous quartzite
JNU 2	146.34	150.91	Compact mica schist
JNU 2	150.91	169.2	Compact mica schist and quartzite
JNU 2	169.2	182.92	Compact mica schist

The lithology of primary drilling Sites Site 1 (JNU1) and Site 2 (JNU2) within JNU shows excellent aquifer has been encountered from 60mbgl down to 96mbgl. The litholog (Table.3) as well as compressor test in the field has further confirmed the high potential aquifer in this area. X-Ray and ICPAES a result shows that at a deeper level water quality remain excellent as in the upper level. At the depth 108.5mbgl the mineral peak shows mainly quartz with some accessories of calcium carbonate. Down to 146.34mbgl the fractured quartzite further shows another good layer of aquifer (Figure 5 and Figure.6). Beyond ferrugenous quartzite at depth of 146 to 150mbgl the compact mica schist shows some garnet crystals in thin section petrography. The presence of garnet in mica schist is suggestive of high grade metamorphism which is further supported by X-Ray and ICPAES investigations. The presence of Barium is decreasing from 4.57mbgl to 77.74mbgl which is suggestive of the selective chemical mobility of the ions during metamorphism leading to pegmatisation.

The presence of different mineral studied in thin section under the petrological microscope, ICPAES and X-Ray diffraction confirms the presence of zoned pegmatite in this area. Groundwater quantity and quality in this area is dependent on grade of metamorphism i.e. pegmatisation and its structural anomaly. Presence of Barium Feldspar forms a weak zone through which the fractures have been developed down to 4.57 to

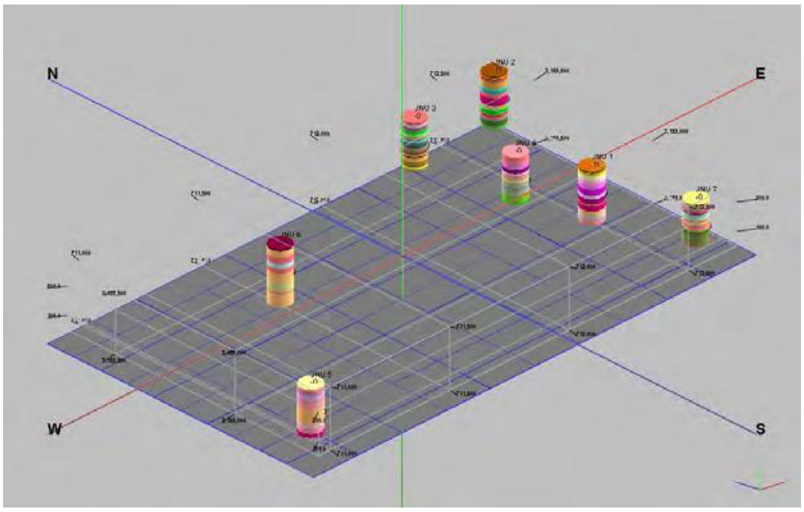


Figure.7 3D interpretation of drilled litholog in a part of NCR (JNU)

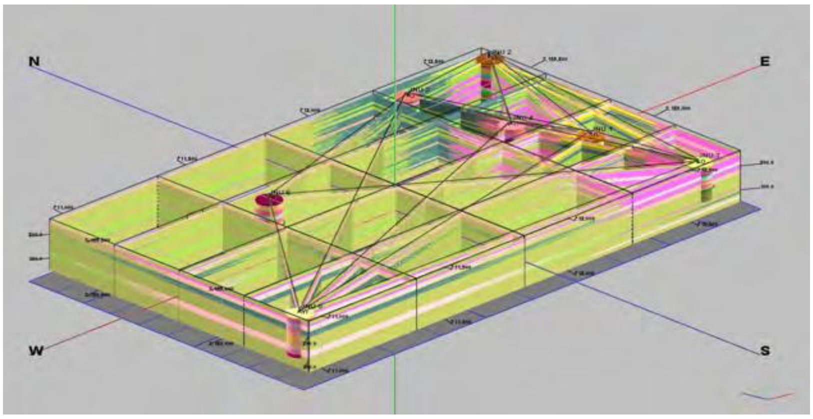


Figure.8.Fence Diagram in a part of NCR (JNU) showing litholog

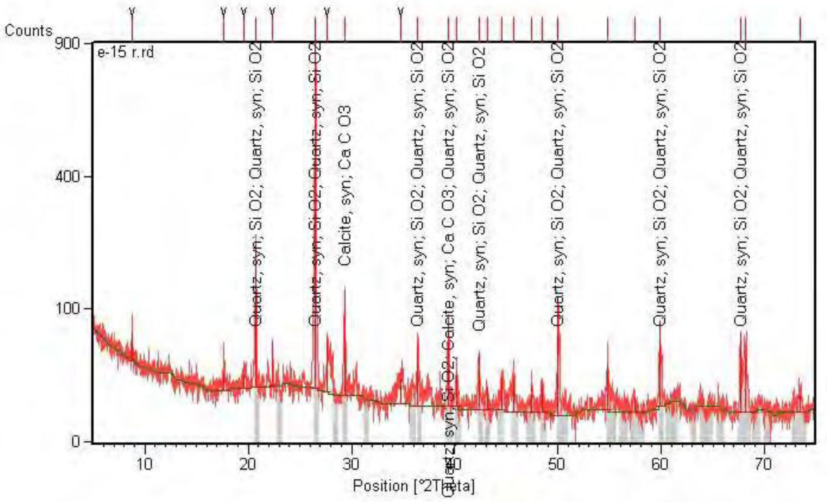


Figure.9.Mineral composition in JNU at 3.25 m bgl.

77.74mbgl(Table.4). Groundwater estimation in this area is highly depend on mineral paragenesis and induced structural anomaly in this area.

Drilling at Site 2 (JNU 2) went up to 182.92metres depth. Here also upper layers up to 9metres depth (approx.) were composed of silt and clay. This was followed by several layers of sand and ferruginous quartzite. Zone around 36-40metres depth marked the transition to mica schist dominant layers (Figure.7).

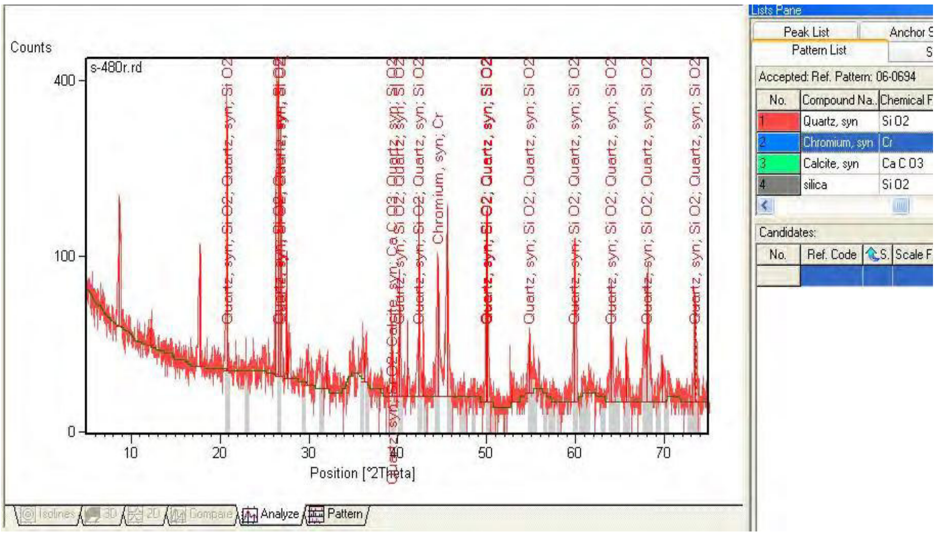


Figure.10.Mineral composition in JNU at 82 m bgl

Sub-surface lithological information was used to generate a lithology solid model for drilling sites predicting the possible sub-surface lithological connections and extrapolating the information to the whole region apart from primary drilling sites. The software (Rockworks) determines the lithology types along each borehole in the project, and assigns certain values to those nodes along the wells. It then uses the "lithoblending" method to assign lithology to nodes lying between wells(Figure.8). Finally, it will reset those nodes above the ground surface to a value of 0.

Three dimensional fence diagrams generated for the part of study area covered by 7 drilling locations shows that top layers in most parts are predominantly composed of Weathered/Fractured Ferrogenous Quartzite. On the other hand the lower layers throughout this part of study area are mostly composed of Mica Schist and Compact Quartzite.

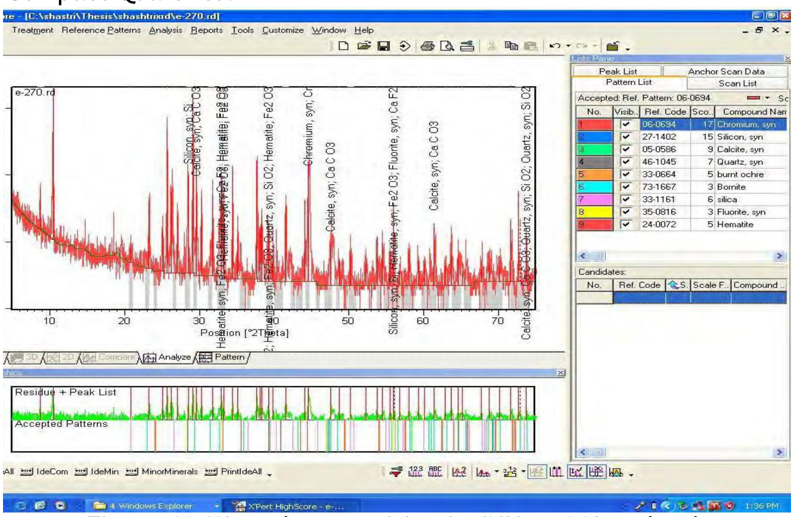


Figure.11.Mineral composition in JNU at 146 m depth

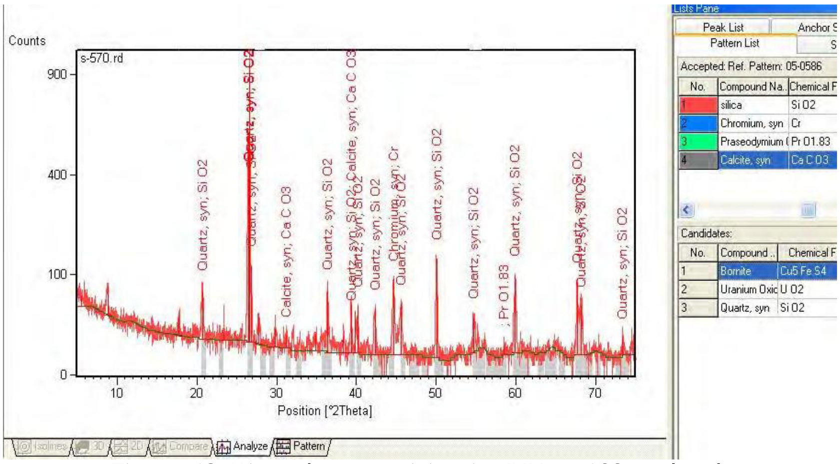


Figure.12.Mineral composition in JNU at 183 m depth

Table.4.ICPAES data of site1 at various depths

	Site1		
Element	**E-75(M)**	**E-90(M)**	**E-133(M)**
Major Element (%)	85.8	86.3	90.8
SiO_2 (%)	43.6	43.8	66.1
Al_2O_3 (%)	13.9	13.8	11.8
Fe_2O_3 (%)	9	9.7	5.1
CaO (%)	11.2	9.8	1.9
MgO (%)	6.8	7.3	1.2
K_2O (%)	0.7	1.2	3.5
MnO (%)	0.08	0.07	0.11
TiO_2 (%)	0.52	0.61	0.5
P_2O_5	495ppm	426ppm	425ppm
Li	<10ppm	<10ppm	<10ppm
Be	2ppm	2ppm	2ppm
B	40ppm	43ppm	102ppm
V	251ppm	272ppm	51ppm
Cr	410ppm	397ppm	42ppm
Co	49ppm	54ppm	9ppm
Ni	131ppm	120ppm	43ppm
Cu	37ppm	24ppm	32ppm
Zn	30ppm	33ppm	18ppm
As	<20ppm	<20ppm	<20ppm
Sr	52ppm	42ppm	37ppm
Y	<20ppm	<20ppm	<20ppm
Nb	26ppm	27ppm	25ppm
Mo	<5ppm	<5ppm	<5ppm
Ag	<1.0ppm	<1.0ppm	<1.0ppm
Cd	6ppm	7ppm	<2ppm
Sn	<20ppm	<20ppm	<20ppm
Sb	<10ppm	<10ppm	<10ppm
Ba	264ppm	124ppm	400ppm
La	<20ppm	<20ppm	27ppm
Ce	<10ppm	<10ppm	102ppm

	Site1		
Element	**E-75(M)**	**E-90(M)**	**E-133(M)**
W	<10ppm	11ppm	12ppm
Pb	37ppm	35ppm	20ppm
Bi	31ppm	31ppm	18ppm
Zr	301ppm	144ppm	119ppm

Summary and Conclusion

The land use of National Capital Region in general and Delhi in particular has gone under drastic change. Change in land use, population growth and seismic instability have all contributed in changing the hydrgeomorphology of NCR. Besides water resources, the growing awareness about the mountain ranges and the alarm of environmental degradation has forced the administration of NCR to arrest the deteriorating environment. The present work can help contribute its mite in mitigating looming ecological crisis. As has been said earlier that this work aims at hard rocks, colluvial and alluvial aggregates for exploration, exploitation and management of water resources. It required a geo-scientific database of water resources for generation of development plans for optimal use of potential resources. Although it is difficult to make all information relating to subsurface water available at one place, nevertheless the present study attempts to give a clear evaluation of a part of National Capital Region. To achieve above a systematic approach of understanding the terrain characteristic at a regional level and then going for detailed mapping by using geological, geophysical, drilling and analysis of drill cuttings and groundwater samples have been adopted. Remote sensing and GIS is used here which has emerged as the most optimal means for monitoring and management of water resources on global, regional and local scale. Being at higher elevation of NCR region with such condition i.e. fault zones, groundwater bearing fracture system and buried pediment plains, major part of the study area has become ideal recharge zone for better groundwater conditions. At higher elevations drainage system which follows the structural lineament and fault zone limit the capacity to hold and retain surface runoff of the rainwater.

An approach was made by drilling in Aravalli in seven locations in a part of JNU and four locations in Research and Referral Hospital. Information from the drilled litholog was correlated with resistivity, magnetic and attributes of NDVI from satellite data. Analysis of drilled logs and groundwater samples from different zones were done to correlate these data with remote sensing geological and geophysical information. These data along with ancillary information were analysed in Arc/GIS software for attribute data creation, derivation of secondary maps of groundwater prospects and quality zonation.

For the present investigation satellite data IRS 1C, IRS 1D (LISS III), Resourcesat and Landsat were used. For geo-referencing Survey of India toposheets and NATMO maps has been used. The data collected from different sources have been used as ground truth information for the preparation of various thematic maps. Detailed ground truthing has been carried out in some selected points of study area. These ground truthing includes resistivity and magnetic surveys and drilling by Down the Hole Hammering (DTH) rig. This process involved following steps:

- Interpretation of data available (Geophysical, Geological, Geochemical, Soil texture and Drilling) for locating suitable groundwater exploration points.
- Interpretation of IRS, Resourcesat, SPOT, and Landsat data for demarcation of groundwater zone including its quality.
- To identify the structural control of the area through Digital Elevation Model generated Shuttle Radar Terrain Mission (SRTM).
- Interpretation of lineament and fracture system in the NCR region.
- Collection of samples for detailed geochemical and petrological analysis.
- Confirmation of recently identified groundwater zone based on distinct vegetation anomaly and lineament fabrics depicted on satellite images.
- Identification of possible groundwater zones based on drilling data.
- Identification of groundwater quality based on NDVI attributes.

It has been observed through field investigations that the interconnected fracture in Aravalli quartzite has been found to have potential for groundwater exploration. Within Aravalli quartzite the ferrugenous variety was found more fracture prone. Pegmatites, Aplite and Quartz vein intercalated with schistose rocks has multiple fracture system. Thin section analysis of rocks from different depth zones shows that the grade of metamorphism has relevance with groundwater quality and potentiality(Figure.8,Figure.9,Figure.10 Figure.11 and Figure.12).

It has been observed that from Aravalli quartzite to river Yamuna there are three prominent watershed boundaries in existence. The buried pediment plains and alluvial plain boundary is demarcated by a very thick layer of fine grained sediments. Hydrogeomorphologically this boundary is not suitable for groundwater exploration.

Elemental composition (rock analysis) of the selected rock samples were analysed by ICPAES. The rock sample represents potential fracture zones encountered during groundwater exploration. The analytical data reveals the following features.

- In all the drilling sites silica content increases with depth which is suggestive of good to excellent groundwater quality at depth.
- Concentration of Al_2O_3 decreases with depth which is also suggestive of excellent groundwater quality.
- Concentration of Zr is found higher in upper zone (245ppm) which reduces to bare (<20ppm) at greater depth this suggest that emplacement of pegmatities are near the surface which is overlying on fractured quartzite at greater depth.

The conclusions inferred from the research work more than eloquent i.e. it was found that wherever the lineament density were high there were also resistivity and magnetic anomaly with lower values. At all those places groundwater available in large quantity. If Normalized Differential Vegetation Index is high, the vegetation is thick due to high moisture laden lineament which is suggestive of high mineral availability and hence the groundwater availability. Wherever there has been excessive use of land, it is difficult to find out the contours of the lineaments. Whereas the lineaments of the unperturbed lands can be easily brought to light.

Resistivity survey threw light on the different levels of water availability. One could infer from photomicrograph of rock shreds obtained during drilling that high grade metamorphism which has not disturbed the aquifers. Since all the aquifers are situated at great depth, they are beyond anthropogenic perturbations. On the other hand alluvial aquifers are more prone to anthropogenic pollution as they are shallow and therefore not potable. Further, it was found that wherever there has been change in the landuse the natural recharge potential too has declined. Digital Elevation Model (DEM) could tell us about the course of water run-off and it will help in recharging the aquifer. The study also came to the conclusion that wells may not be directly recharged. There can be indirect method of recharging them. Recharging the lateral dry wells can be done by the lateral homogeneity. In view of total area of study in JNU which is approximately 5sqkm the number of tube wells were restricted to seven based on the delineation of micro-watershed. As per the National Water Policy there should not be more than one tube well in one micro-watershed. The research work carried out recommends that there should not be further drilling in JNU area for sustainable performance of the aquifers. Although the discharge of the tube wells are ranging between 24,475 Lt/hr to 34,125 Lt/hr with less than 10mts draw down in 72hrs of pumping but it is recommended that the groundwater can be pumped from the tub wells for 8Hrs then it should be allowed to recover for 5hrs. In this area most of the drilling site fractures are interconnected with high transmissitivity, it has been observed that 80% recovery of draw down takes place within 1hr, if surrounding tube wells are also stopped. Remaining 20% recovery takes 4hr due to elastic nature of the aquifer. Hence it will be safer if the tube wells are not pumped together with more than 8hrs. If the above recommendations are not followed and tube wells are operated continuously then it may result in permanent decline of groundwater level.

Similar work has been done from Remote Sensing Laboratory, SES, JNU in Humanyun Tomb, IGNOU and Research and Referral Hospital areas. The result and effect is arrest of lowering down of the water level in the areas mentioned above further supports the lateral recharge hypothesis in confined aquifers.

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