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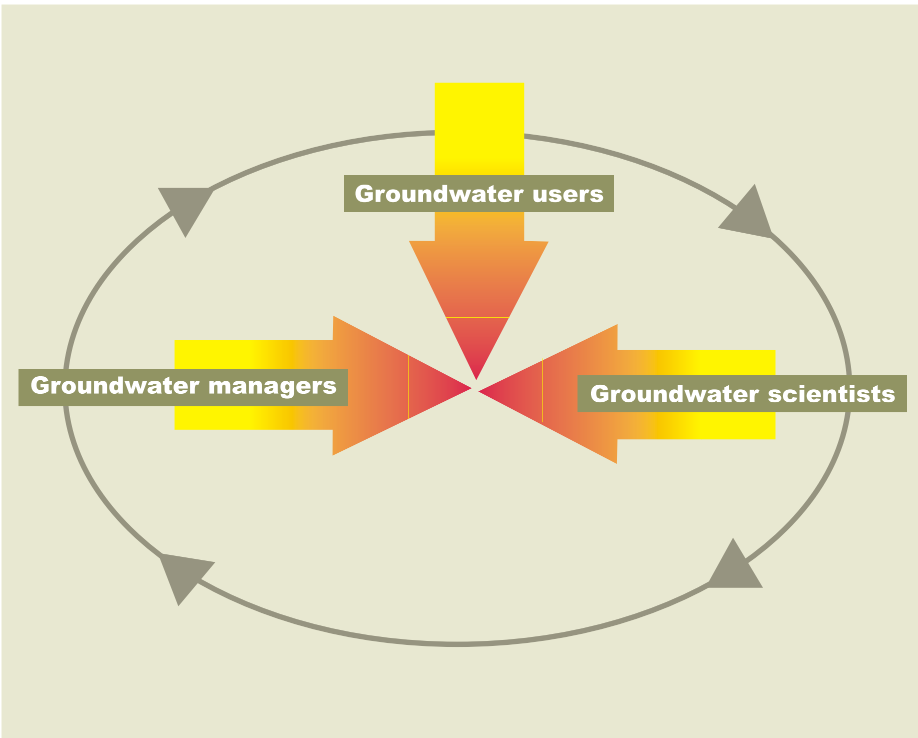
Groundwater Research and Management: Integrating Science into Management Decisions

Bharat R. Sharma, Karen G. Villholth and Kapil D. Sharma, editors



Groundwater Management Research Alliance

International Water Management Institute

GROUNDWATER GOVERNANCE IN ASIA

IWMI-TATA Water Policy Program

National Institute of Hydrology

Groundwater Research and Management:
Integrating Science into Management Decisions

Groundwater Governance in Asia Series

Groundwater Research and Management: Integrating Science into Management Decisions

Proceedings of IWMI- ITP- NIH International Workshop on
"Creating Synergy between Groundwater Research and Management in South and Southeast Asia"

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Preface

"Groundwater will be the enduring gauge of this generation's intelligence in water and land management"

Australian Groundwater School, Adelaide

Sustaining the massive welfare gains that groundwater development has created without ruining the resource base is a key water challenge facing the world today. Significant populations of South and Southeast Asia have come to increasingly depend on groundwater for use in agriculture as well as other economic sectors, including for domestic supplies. Small holders in developing agrarian economies of India, China, Nepal, Bangladesh and Pakistan have huge stakes in groundwater irrigation, because it has served as one of the largest and most potent poverty reduction programs in recent decades. However, this sudden boom in groundwater development has also triggered the secular and seasonal groundwater level declines, wells running dry and well failures, rising energy use and pumping costs, weakening drought protection, salinity ingress in coastal areas and health hazards due to arsenic, fluoride or other naturally inherent, -toxins or waste-or agriculturally derived chemicals and these impacts are seriously threatening the long-term sustainability of the use of the resource.

When it comes to solving the problems, and putting into place effective management strategies, the impediments are many. Protecting the resource is often in direct and immediate conflict with strategies of livelihood support to rural poor and presents the most complex resource governance challenge. There also appears to be a general disconnect between the efforts of various technical and non-technical specialists of groundwater resource disciplines. There is a strong need to close the gap between the perceptions and understanding of the groundwater managers and scientists to soften up their traditional roles and to improve the appreciation of the significance of mutual understanding of roles and of communication. It was with these objectives in mind that International Water Management Institute (IWMI), IWMI-Tata Water Policy Program and (Indian) National Institute of Hydrology (NIH), Roorkee organized a two-day International Workshop on "Creating Synergy between Groundwater Research and Management in South and Southeast Asia" during 8-9 February 2005 at the beautiful campus of National Institute of Hydrology, Roorkee, India. Technical and management professionals from Bangladesh, China, India, Nepal and Pakistan and resource persons from other international organizations presented well articulated commissioned papers and country reports covering major aspects of the science and management of grountwater. Summary of the workshop proceedings and major recommendations are given in first chapter of the volume followed by edited versions of the country reports and groundwater issue papers. This publication (first in the Groundwater Governance in Asia (GGA) Series) is a humble endeavor to achieve the workshop objective of bringing together key researchers and managers within groundwater in Asia and synthesize their knowledge, perceptions and ideas for improved groundwater management and research within the region.

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Karen G. Villholth
Kapil D. Sharma

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National Institute of Hydrology (NIH), Roorkee, India.

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Workshop participants and notably those who presented papers, Session chairpersons and organizers/ facilitators.

Keynote Speaker: Tushaar Shah, IWMI, ITP, Anand, India.

Creating Synergy Between Groundwater Research and Management in South and South East Asia

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Abstract

Groundwater is under increasing threat from over-development, over-extraction and pollution, due to increasing population pressure, increasing living standards, industrialization, and a lack of proper management to match the demands and use patterns with the natural resource base. This is a global trend, and though regional differences exist this is no exception in South Asia and South East Asia. This introductory chapter gives a brief summary of the chapters included in this volume. It sets out by highlighting the major issues and challenges related to groundwater research and management followed by specific issues faced by five Asian countries with relatively high rates of groundwater development and associated environmental and socio-economic implications during recent history (India, China, Pakistan, Bangladesh and Nepal). Then more specific cases and approaches to groundwater assessment and management in the region are briefly described, giving broad indications of the situation in particular areas and how challenges are being approached from various sides. Though many trends and circumstances are similar across the countries, some particular problem areas are more pronounced and need special attention in the different parts. It is also clear that the complexities involved are many and diverse and solutions cannot be found without a multi-disciplinary approach, involving the triangle of stakeholders: the groundwater and land users, the scientists and the managers.

Introduction

Groundwater has been developed in the South and South East Asia primarily during the last 40 years (Table 1). The rate and scale at which this has, and still is, occurring is so intense that it is causing concerns, not only within the countries themselves, but also at an international level. This is because unsustainable groundwater use potentially influences livelihoods and food security for huge numbers of people dependent on groundwater for subsistence or commercial farming in these regions (many millions of people) as well as potentially influencing international food trade and associated policies.

Groundwater problems emerge slowly and incrementally, as the cumulative effect of many individual impacts of abstractions and contamination sources manifest themselves. The impacts are also delayed as the 'transmission time' of any impacts (lowering of groundwater tables and pollution spreading) to surrounding and downstream areas are long. Conversely, the timescales for remediation are also long, and impacts noticed today will persist for some time, even after the reversal of the original stresses. Hence, emerging problems, which are indeed evident in many parts of these countries today, need to be taken seriously and confronted with a degree of priority (Burke and Moench, 2000). Without going into detail, but referring to the following chapters for details, the impacts manifesting themselves are:

- Continuously dropping groundwater tables with ramifications on economic pumping feasibility, inequity in access to the resource by different population segments, and drying out of significant associated groundwater-dependent water bodies and ecosystems.
- Saltwater entry into wells, from various courses and sources, like seawater intrusion in coastal areas, geo-genic[1] saltwater from geological formations, and salinization from reentry of saline drainage waters or mismanagement of irrigation systems in arid areas.
- Contamination of wells from human activities, like agriculture, waste disposal and wastewater discharge.
- Contamination of wells from geo-genic toxic or unwanted elements, like arsenic, fluoride, and iron.

As groundwater availability is less dependent on recent rainfall due to its longer-term storage capacity, groundwater plays a key role in drought protection and drought resilience. However, if groundwater is being overexploited leading to drawdown of groundwater levels there is a limit to this drought buffer capacity, and in fact droughts become the periods where problems of groundwater over-exploitation become more evident and felt among its users.

The International Workshop on "Creating Synergy between Groundwater Research and Management in South and Southeast Asia" held during February 8-9, 2005 at the campus of National Institute of Hydrology, Roorkee, India conducted its deliberations through paper presentations and plenary discussions to highlight the major issues concerning groundwater assessment, development and augmentation, utilization and contamination and above all the management and governance of the resource in the Asian context. This was followed by state of the art country papers from Bangladesh, China, India, Nepal and Pakistan. An overview of the important issues deliberated during the workshop and a summary of the issues raised under the country papers is given below. Sincere thanks are extended to the authors and session rapporteurs, from whose reports we borrowed heavily in drafting these sections.

Global Groundwater Use

Global groundwater use is about 1000 km^3/year, which is around 8.2 per cent of annually renewable groundwater resources (Shah, 2000), but its contribution to human welfare is huge. India, China and Pakistan alone account for one-third of global groundwater use.

[2]Deriving internally from the aquifer material.

Globally, growth in groundwater irrigation has had little to do with the occurrence of the resource, as its intensive development has tended to occur in arid and semi-arid regions with relatively poor groundwater endowments. There appears to be a good correlation between high population densities and high tubewell densities in India, Pakistan, Bangladesh and China. India alone is adding about 1 million new tubewells every year since the last 15 years and there is no sign of deceleration (Shah et. al., 2003). In poor developing countries, protection and conservation of groundwater resources is often in direct and immediate conflict with livelihood support to rural poor and in meeting domestic needs of towns and cities and thus presents the most complex resource governance challenges facing the world's water professionals.

Summary of Country Chapters

The country reports (Chapter 3-9) describe the current groundwater situation in India, China, Pakistan, Bangladesh and Nepal along with significant trends over the past half century. They also point to important challenges and responses emerging as well as recommendations for further efforts.

From looking at the figures of these chapters, of which the most salient ones are summarized in Table 1, it appears that the groundwater dependence, in terms of numbers of people dependent on groundwater, primarily for agriculture, and in terms of amounts of water extracted for irrigation decrease in the order: India, China, Pakistan, Bangladesh and Nepal. This order is only meant to give a sense of the relative scales involved, but of course groundwater use and associated problems are more pronounced in some parts of these countries than in others.

Even higher numbers of people are dependent on groundwater in these countries than apparent from Table 1, namely for their drinking water and other domestic uses. However, the amounts of water required to satisfy these demands are relatively small compared to water requirements within agriculture and hence the water use within agriculture and how it is being managed is crucial to the overall sustainability of groundwater, which justifies the focus on agriculture. Nevertheless, groundwater use for domestic purposes has overriding importance in public health and well-being and should not be overlooked. And in fact, there is often a disregard of the close links between domestic (ground) water use and the use for agriculture. Groundwater developed for agriculture is often used in the households, and impacts due to mismanagement of water and land use within agriculture often has direct consequences for the availability, reliability and quality of domestic water sources and hence the prosperity of farming communities.

Significant Similarities

The stories of the five countries are to a large extent similar and parallel. Significant groundwater development started in the 1970's, with the introduction of tube well and pumping technology, rural electrification and demand for increasing crop production due to population increases, both for sustaining growing cities but also for a growing rural population. Groundwater development has occupied an important place in poverty alleviation policies because of its role in stabilizing the agriculture and ensuring food supplies and livelihoods for farmers of which many are in the lower brackets of household income. Groundwater scarcity translates directly into lack of secure food supplies and livelihoods for many rural farmers with previous easy access to groundwater. So, on one hand groundwater is (or has) created wealth and poverty reduction in rural areas.

Table 1. Key figures for groundwater use in agriculture in five major groundwater using nations in South and South East Asia[3]

Parameter	India	China	Pakistan	Bangladesh	Nepal
Percentage of population whose livelihood depend on agriculture	70%	59%		about 85%	86%
Percentage of population dependent on GW for irrigation	55-60%	20-25%	60-65%	about 64%	
No. of people dependent on GW for irrigation, million	586-639	257-321	89-96	85	
No. of GW structures, million, recent data (year)	20 (2005)		0.60 (2005)	0.95 (2001)	0.86 (2005)
No. of GW structures, million, previous data (year)	4 (1951)			0.15 (1985)	
No. of GW structures used in agriculture, million			0.68	0.9	0.06
Percentage of GW structures used in agriculture			97%	30-35%	7%
Percent of total water withdrawal derived from GW		20%	33%	75%	
Percent of GW withdrawal used for agriculture			46%	70-90%	6%
Percent of irrigation water from GW	70%		35%	75%	
Cultivated land, M ha		123.4	16		2.4
Irrigated area, M ha		49.1	14.3	4	0.92
Percentage of cultivated land irrigated		39.8	89.4		38.1
Irrigated area, irrigated by GW, m ha	45.7		3.45	3	0.21
Irrigated area, percentage served by GW	70%		73%	75%	23%
Start of GW irrigation boom	1970's	1980's	1970's	1970's	1970's
Total annual GW recharge, BCM	432	884	83		8.8
Net annual GW availability, BCM	361	353	70		
Total annual GW draft, BCM, recent data	150	112	68		1.1
Total annual GW draft, BCM, previous data		57	10		

[3] The table includes primarily data derived from the chapters of this volume. Missing data does not imply that information does not exist but rather that it was not reported in these chapters.

On the other hand, and increasingly, groundwater problems hit disproportionably hard on the poor people. This generates an obvious impasse for politicians and managers, creating inertia towards actively addressing the groundwater problems. It is only within the last decades that researchers have analyzed the trends and warned against the lack of commitment to emerging groundwater issues and politicians and managers have become sensitive and started reacting.

This development in groundwater exploitation has been termed a 'groundwater boom' or 'groundwater rush', implying that it is not sustainable and that eventually the rates of exploitation will have to level off and/or decrease. The problems are manifesting themselves to various extents in all of the five countries, but it should be kept in mind that the problems are not always directly associated with the groundwater use itself.

Groundwater level declines are of course most often associated with the direct over-use of groundwater but contamination of groundwater is often not an effect immediately associated with the use of groundwater. As an example, much groundwater is being contaminated due to the agricultural practices followed in intensive agriculture be it irrigated with groundwater or not. Also, the increasing production of wastewater, especially from large cities in these countries is posing severe problems for the overall ambient water quality, both in surface waters and groundwater due to the limited treatment capacity of many cities. Dumpsites and other types of waste disposal on the land is another source that increasingly has to be attended to in order to alleviate groundwater problems of these areas.

In general, there is an increasing concern over the deteriorating quality of groundwater in many parts of these countries, though the trends are not always quite well documented, and it is progressively being realized that without proper attention to the groundwater quality aspects we will not be able to solve long term threats.

Significant Differences

Before the groundwater boom, groundwater was lifted by simple mechanical or manual methods. However, for modern groundwater irrigation, a source of energy for lifting water is essential, either fossil fuel (diesel or petrol) or electricity. Hence, the linkage between the energy for lifting groundwater and irrigation economics is very important and this link is increasingly being realized as a potential mechanism for controlling the rates of groundwater extraction in agriculture. In parts of the Nepal terai and parts of India (North eastern parts), the lack of rural electrification is an impediment for efficient utilization of groundwater (Chapters 8 and 15) . In other regions, the limit to pumping is given by the number of daily hours of electricity supply, and basically farmers pump continuously if they have the possibility. Subsidies to irrigation through free or cheap energy have been a tool for enhancing groundwater irrigation development. Still only little actual and pro-active efforts have been put into suspending some of these benefits, in favor of saving on groundwater resources though India is playing with various models at the pilot scale (Chapter 18). In China, electricity is controlled better (in terms of supply and revenue collection) and here more concrete attempts of limiting groundwater pumping through supply and economic incentives have been implemented (Chapter 4).

In general, it appears that India and China may be addressing their groundwater problems quite differently. India has invested huge sums in watershed development programs in which components of groundwater recharge are very significant. Also, many activities to recharge groundwater at local scales are of private or collective nature and have in places turned into almost spiritual movements trying to 'quench the thirst of mother earth'. In China, the trend has been more towards privatization of irrigation and wells and trying to implement more bureaucratic measures for groundwater control. Large efforts and hope for water saving irrigation have been raised, but whether these technologies are relieving stress on groundwater is far from clear. China is facing increasing groundwater demands from growing cities and the conciliation of water use in agriculture vs. a growing industrial society is a major challenge.

Pakistan is mainly struggling with the optimal and conjunctive use of its surface water and groundwater resources, the ever-lurking salinity problems and a number of large cities outgrowing the present supply of water (Chapter 9). Since these cities are far upstream in the Indus river basin wastewater flows that cannot be treated with the present capacity poses major threats on surface and groundwater.

Bangladesh also faces the challenge of optimizing surface and groundwater, with huge seasonal differences in surface water availability and limited infrastructure and institutions for storing water and developing and maintaining irrigation (Chapter 3). The one overriding problem of groundwater in most of Bangladesh is the natural presence of high levels of arsenic in shallow groundwater. This is increasingly limiting the sustainable use of shallow aquifers for drinking and even for agriculture.

Nepal is the country in which groundwater is least developed, and still presents a huge potential for lifting the rural population, mainly in the *terai*, out of poverty if properly managed (Chapter 8). Arsenic maybe a black joker in these aquifers, but the picture is still not clear. In the Kathmandu Valley, groundwater development has already reached its potential and signs of over-exploitation are evident.

Groundwater Modeling and Optimization

The issues related to development, protection, restoration, and remediation of groundwater resources are very complex. Proper understanding of aquifer behavior in response to imposed or anticipated stresses is required for designing and implementation of management decisions. Groundwater management strategies should be directed towards balancing the demand with the fortune of supply. Groundwater modeling is one of the management tools being used in the hydrogeological sciences for the assessment of the resource potential and prediction of future impact under different stresses/strains. There are numerous codes of groundwater models available worldwide dealing with a variety of problems related to flow and contaminants/pollutants transport, rates and location of pumping, natural and artificial recharge and changes in groundwater quality. Each model has its own merits and limitations and hence no single model may be universally applied. Management of a system means making decisions aiming at accomplishing the system's goal without violating the specified technical and non-technical constraints imposed on it. A complete groundwater management model thus is the combination of a groundwater simulation model and a resource optimization scheme. It is through simulation models that one can integrate groundwater science into the management options to understand and evaluate the potentiality and the fate of the resource for different options and constrained situations. These models thus help the resource managers and decision makers to transform or mediate a supply driven groundwater development into an integrated groundwater resource management through integration of supply-side management with the demand-side constraints.

Application of such simulation models and optimization studies for the aquifers of northwest India has been quite helpful (Kaushal and Khepar,1992). High yielding intensive irrigated agriculture (mainly rice and wheat) based on indiscriminate exploitation of groundwater has led to continuous decline of the water table in freshwater areas, with deterioration of water quality, water logging and soil salinity in the saline groundwater bearing areas. Such a scenario of falling/rising water table is threatening the sustainability of irrigated agriculture in the these areas, the food bowl of the country. Simulation modeling and optimization studies indicated that if the present trend of excessive pumping of groundwater through installation of various structures continue, it will not be possible to pump groundwater by centrifugal pumping system because of a continuous fall in groundwater table. The farmers will have to install submersible pumps at a very high cost. An available management option was to decrease the area under paddy or reduce the pumping in that area and meet the remaining irrigation demand by transfer of canal water from rising water table areas to the declining water table area. In case of rising water table areas, the adoption of conjunctive use practice of surface and poor quality groundwater coupled with efficient irrigation application systems can help in managing the water table conditions and sustaining agricultural production in these regions

Safe Use of Saline Groundwater Resources

Future reductions in freshwater supplies to agriculture will induce farmers to look for non-conventional water sources, e.g make greater use of saline groundwater resources. Saline groundwater occurs extensively (32-84% of the underlying shallow groundwater resources) in the arid and semi-arid environments of India and Pakistan and other countries (Sharma and Minhas, 2005; Qadir et. al., 2006). Persistent research efforts have demonstrated the possibilities of using such waters through selection of salinity resistant crops, crop varieties and cropping patterns while maintaining low levels of salts in the active rhizosphere through appropriate irrigation schedules, application methods and conjunctive use of groundwater, canal and rainwater and optimal use of chemical amendments and land configurations to mitigate harmful impacts (Minhas, 1996).

Decisions regarding conjunctive use of saline and freshwater resources and allocation of water based on economic returns and tolerance to salinity is a complicated process and is best attempted through numerical modeling. Such a model shall maximize net benefits from use of waters of varying salinities through allocations to different crops and determine the optimal groundwater pumping for irrigation and drainage water disposal. The allocation of poor quality water essentially centers on crop-water-salinity production functions, which are non-linear in nature. For economic optimization of the conjunctive use, salinity resistant cash crops (cotton, mustard, horticultural crops) may find favor over traditional cereal crops. Conjunctive use of saline groundwater with canal water on sustained basis will also require disposal of some part of saline water through evaporation ponds and regional drains.

Establishment of water quality monitoring networks, modification in canal water delivery schedules, and suitable water and energy pricing and promotion of micro-irrigation systems are required to better use the saline groundwater resources (Tyagi et. al., 1995). Efforts are needed both at farmers' level as well as at government level to realize potential gains of conjunctive water management.

Groundwater Augmentation

Watershed based development has been accepted as a key strategy for ensuring sustainable management of land, water, vegetation and human resources for improved productivity in rainfed areas. Water harvesting and groundwater recharge are principal components of most of such development interventions. In many parts of hard-rock regions of India, groundwater depletion has invoked widespread community-based mass movement for rainwater harvesting and recharge, e.g. in eastern Rajasthan, Gujarat, Madhya Pradesh and Andhra Pradesh states of India (Sharma et. al., 2005). Protagonists think that with better planning of recharge structures and extensive coverage, the decentralized recharge movement can be a major response to India's groundwater depletion because it can ensure that water tables in pockets of intensive use rebound close to pre-development levels at the end of monsoon. India's Central Groundwater Board has developed a national blueprint for groundwater recharge in the country which aims at recharging surplus runoff of about 36.4 billion cubic meters in an area of about 450,000 sq km identified in various parts of the country experiencing a sharp decline in groundwater levels (CGWB, 1996). Using this opportunity would require investing in creating scientific capability and infrastructure for groundwater recharge as a top priority for regions with excessive pumpage and significant renewable water resources.

Institutional Credit for Groundwater Development

In India alone, farmers have installed about 20 million groundwater abstraction structures by government support through institutional credit and subsidies to electricity and diesel to run the pumps. Institutional credit of about USD 5.2 billion/annum is made available for both private (individual) and community owned dugwells, tubewells, irrigation pump sets, energization, river lift irrigation schemes and associated infrastructure such as pipelines, irrigation systems and tanks. This credit is duly supported by subsidy provided by central and state governments to promote and popularize minor irrigation investments amongst farmers. However, there are large regional variations in implementation of the programs as certain areas in the northwest and south overexploited the resource and institutional credit has to be stopped in 'dark' and 'critical' blocks, whereas there were few takers for the credit in the eastern region due to small and scattered holdings and very weak governance and infrastructure systems. Sizeable numbers of small and marginal farmers also do not have access to institutional credit because of fragmented land holdings, cumbersome procedures and documentation and delays in subsidy and loan disbursement. Several evaluation studies have found that institutional credit and private investments become attractive only when farmers opt for diversified agriculture based on high value crops. Inadequate and unreliable energy supplies in rural areas coupled with populist schemes of free/subsidized energy seriously affects the equitable distribution of benefits of groundwater and poor and small farmers get marginalized. Uneconomic pricing of energy has also resulted in unwarranted, exaggerated and sub-optimal use of groundwater leading to adverse environmental impacts and low productivity in agriculture.

Groundwater-Energy-Agriculture Policies Nexus

Energy and water are key inputs to agricultural production and their inter-linkages pose significant management challenges. Lack of appropriate energy policy and policy to deal with management of groundwater has not only contributed to over-exploitation of groundwater, it has also resulted into a nexus (Shah et. al.,2003). Perverse incentives provided as part of the energy policies have lead to inefficiency and almost financial bankruptcy of the energy utilities. However, further and deeper analysis of the nexus shows that growth in use of groundwater and energy for pumping coincides with the overall development policy of attaining food security. Agricultural policies, especially those dealing with gaps in market linkages for agricultural products and role of minimum assured support price for certain crops by the government, have great influence on farmers' choice of cropping pattern and hence excessive groundwater use.

The Indian Punjab has become one of the most important regions for cultivation of paddy in the country where the state government gives free electricity to the farmers for running their tubewells. Due to large-scale cultivation of paddy, and low recharge of groundwater, the water table has been declining steeply; in certain regions by about 1 m per annum. The water table in large parts of the region has gone down by 30 m during the last four decades (Hira and Khera, 2000) and original shallow tubewells have gradually been replaced with high powered submersible pumps. Efforts to convert a part of the area from paddy to some other crops have met with little success as paddy is more profitable than any other crop and it enjoys a regime of assured procurement at the pre-announced price. The combined effect of these policies has resulted in the hydrological unsustainable over-exploitation of groundwater. Policies governing agriculture and energy (and thus groundwater) are apparently dictated more by political populism rather than sound management strategies for sustainable resource development and utilization. Procurement policy and pricing mechanisms need to be revamped, not just from reducing fiscal burden on the exchequer and from equity perspective, but for long term environmental benefits and livelihood security that can be achieved from efficient utilization of groundwater. Indirect policies of the energy and agriculture sector need to be concurrently approached to bring diversification into agriculture and therefore arresting groundwater depletion, and safeguarding livelihoods and food security.

Integrating Groundwater Science and Management

The inherent characteristics of groundwater, its prevalence and reliability in supply and quality, which lead to its widespread use by millions of small farmers also give rise to major challenges faced by groundwater managers. Effective groundwater resource management requires an optimum balancing of the increasing demands of water and land users with the long-term maintenance of the complex natural resource. Groundwater science helps us to have an accurate assessment of the resource, understand specific susceptibilities of the aquifers to abstraction and contamination and the interactions between groundwater and surface water resources. Management of the resource in addition requires the groundwater managers to appreciate the policies which strongly influence water use and food production, regulatory provisions and their limits for conserving the resource, role of stakeholders at different levels in decision making and the need for development of integrated approaches that balance the needs of the poor and the environment with economic development goals. There appears to be a general disconnect between the technical specialists of groundwater resources and the decision makers challenged with its sustainable use and management. Proper groundwater management requires the integration of science into management decisions. Groundwater scientists and mangers need to have a better and common understanding of some of the routinely used terms like 'safe or sustainable yield', 'groundwater over-exploitation', and the actual role and scope of water saving technologies for resource augmentation. As groundwater resources come under increasing pressure, allocation between various users, including the environment, becomes increasingly complex and the need for sound approaches based on natural, economic and social sciences becomes progressively more evident. There is a strong need to close the gap in perceptions and understanding between groundwater managers and scientists to soften up the traditional roles and to improve the appreciation of communication and mutual understanding of diverse roles. The overall goal should be to form a partnership that ensures that decisions, though pragmatic, are made based on the best available multi-disciplinary scientific knowledge.

Recommendations

Each country paper gives a list of recommendations for improved development and management of groundwater in their context. Summarizing these, and using the framework suggested by Zahid (Bangladesh), they can be classified into the following groups:

i. Monitoring/Data Management

- Strengthen appropriate organizations and frameworks for monitoring the quantity and quality of groundwater on a continuous basis.
- Prepare databases to compile, store and retrieve vital data on groundwater properties and variables necessary to detect significant trends.

ii. Investigation/Implementation

- Perform detailed and precise studies using modern tools to generate relevant and accurate data, which shall ultimately result in a more accurate assessment of groundwater resources.
- Encourage and implement artificial recharge, conservation, water-saving irrigation, conjunctive use of surface water and groundwater, fresh and brackish water, treatment and reuse of wastewater, and land use planning and land zoning as per the availability of water and taking appropriate measures to avoid pollution.

iii. Capacity Building/Awareness Raising

- Enhance public awareness and knowledge of groundwater.
- Enhance capacity building of groundwater centers/institutes and create work environments for better communication, co-ordination, and collaboration among water managers, planners, decision-makers, scientists, water users, etc.
- Present results of investigations and evaluations of groundwater and regional hydro-geological mapping in formats workable enough for examining and approving permits to groundwater abstraction and practical schemes of groundwater exploitation.
- Develop a state of knowledge and capability that will enable the countries to design future water resource management plans by themselves addressing economic efficiency, gender equity, social justice and environmental awareness in order to facilitate achievement of the water management objectives through broad public participation.

iv. Management/Policies/Economic Instruments

- Establish legal and regulatory framework regarding development and use of groundwater.
- Revise policies on subsidized power in the agricultural sector. Suitable cost and charging systems of electricity is to be decided to ensure recovery of operation and management and capital cost and avoid misuse/overuse of power.
- Encourage and involve community organizations to prescribe irrigation charges and to become responsible for collection and imposition of penalties for non-payment.
- In the case of industrial effluent disposal, follow the principle of "polluter pays".

Ways Forward

Though it is realized that priorities may differ depending on individual pressing problems, the historical perspective of groundwater use and management, cultural values and political realities, it is also clear that awareness raising and capacity building is an overriding requirement at all levels in society to enhance the understanding, sensitivity and commitment towards improving the use of groundwater in Asia and other regions.

Furthermore, it is important to make decisions on an informed and qualified basis. To that end, there has to be an increased dialogue and collaboration between managers/decision makers and the researchers. Providing the incentives for both parts to contribute to such a dialogue is crucial and it is humbly hoped that providing forums like this workshop contributes towards this goal. The last, but not least partner in such a triangle (Figure 1) is of course the groundwater users. Informing them and involving them actively in this dialogue is also a key to obtaining sustainable and acceptable solutions to groundwater management challenges.

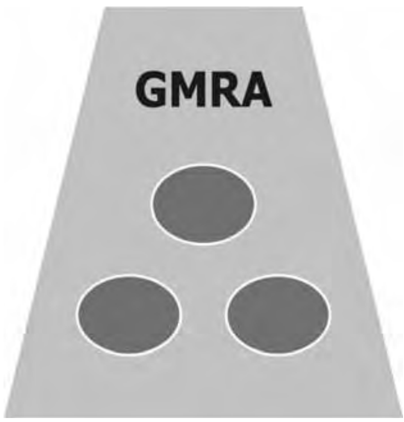

Figure 1. The triangle for a Groundwater Management Research Alliance (GMRA). The dots represent the three parts: groundwater users, groundwater scientists and managers

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Groundwater and Human Development: Challenges and Opportunities in Livelihoods and Environment

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Abstract

At less than 1000 km³/year, world's annual use of groundwater is 1.5% of renewable water resource but contributes a lion's share of water-induced human welfare. Global groundwater use however has increased manifold in the past 50 years; and human race has never had to manage groundwater use on such a large scale. Sustaining the massive welfare gains groundwater development has created without ruining the resource is a key water challenge facing the world today. In exploring this challenge, we have focused a good deal on conditions of resource occurrence but less so on resource use. I offer a typology of 5 groundwater demand systems as Groundwater Socio-ecologies (GwSE's), each embodying a unique pattern of interactions between socio-economic and ecological variables, and each facing a distinct groundwater governance challenge. During the past century, a growing corpus of experiential knowledge has accumulated in the industrialized world on managing groundwater in various uses and contexts. A daunting global groundwater issue today is to apply this knowledge intelligently to by far the more formidable challenge that has arisen in developing regions of Asia and Africa, where groundwater irrigation has evolved into a colossal anarchy supporting billions of livelihoods but threatening the resource itself.

Global Groundwater Juggernaut

Rapid growth in groundwater use is a central aspect of the world's water story, especially since 1950. Shallow wells and muscle-driven lifting devices have been in vogue in many parts of the world for the millennia. In British India (which included today's India, Pakistan and Bangladesh), wells accounted for over 30 percent of irrigated land even in 1903 (http://dsal.uchicago.edu/statistics/1894_excel) when only 14 percent of cropped area was irrigated. With the rise of the tubewell and pump technology, groundwater use soared to previously unthinkable levels after 1950. In Spain, groundwater use increased from 2 km³/year to 6 km³ during 1960-2000 before it stabilized (Martinez Cortina and Hernandez-Mora 2003). In the US, groundwater share in irrigation has increased, from 23 percent in 1950 to 42 percent in 2000 (http://water.usgs.gov/ pubs/circ/2004/circ1268/). In the Indian sub-continent, groundwater use soared from around 10-

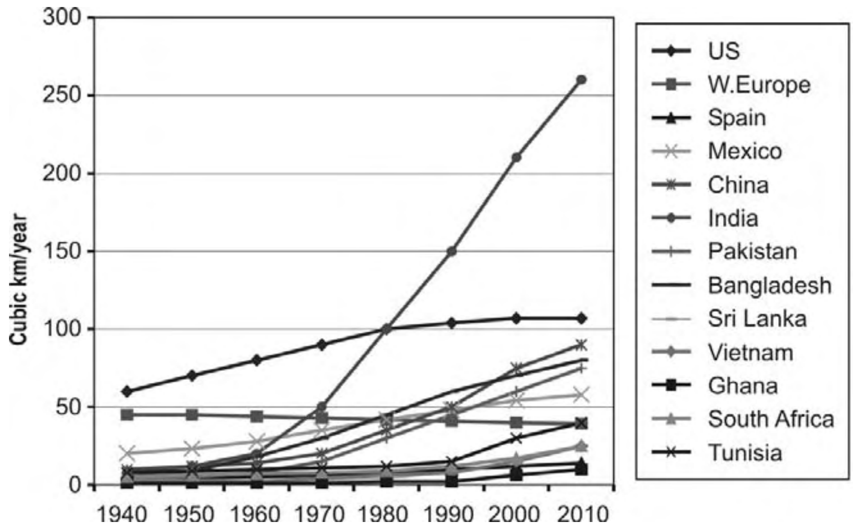

Figure 1. Growth in groundwater use in selected countries (author's estimates)

20 km^3 before 1950 to 240-260 km^3 today (Shah et al. 2003a). Data on groundwater use are scarce; however, Figure 1 attempts to backcast the probable trajectories of growth in groundwater use in selected countries. While in the US, Spain, Mexico, and North-African countries like Morocco and Tunisia total groundwater use peaked during 1980's or thereabout, in South Asia and North China plains, the upward trend begun during the 1970s is still continuing. A third wave of growth in groundwater use is likely in the making in many regions of Africa and in some south and south-east Asian countries such as Vietnam and Sri Lanka (Molle et al. 2003).

Typology of Groundwater Socio-ecologies

At less than 1000 km^3/year, global groundwater use is a quarter of total global water withdrawals but just 1.5% of the world's annually renewable freshwater supplies, 8.2 percent of annually renewable groundwater, and 0.0001 percent of global groundwater reserves estimated to be between 7-23 million km^3. Yet its contribution to human welfare is huge in five distinct types of groundwater socio-ecologies (GwSEs) based on intensive groundwater use, each embodying a unique pattern of interaction between socio-economic, demographic and ecological variables, and each presenting a distinctive groundwater management challenge:

Type I: Habitat support GwSE's

Groundwater has historically supplied water in numerous human settlements, urban and rural, around the world. According to one estimate, "..over half the world's population relies on groundwater as a drinking water supply." (Coughanowr,1994). Seventy percent of piped water supply in EU is drawn from groundwater. Management of Type I GwSEs presents unique challenges since, in the process of urbanization, the population of a habitat generally grows faster than its geographic span; as a result, pressure on groundwater resources underlying the habitat increases rapidly as villages grow into towns and thence into cities. The ubiquitous response combines import of surface or groundwater from a distant source, volumetric pricing, improved water supply infrastructure and service to crowd out private urban tubewells to reduce pressure on urban groundwater.

Type II: Nonrenewable GwSE's

Arid and semi-arid countries in the MENA (Middle East and North Africa) region—Saudi Arabia, Yemen, Jordan, Oman, Bahrain, UAE, Iran, Libya, Egypt—depend on either fossil or limitedly renewable groundwater. Some, such as Saudi Arabia, Jordan, Yemen and Libya experimented with intensive groundwater use in agriculture to secure food self-sufficiency; however, it is increasingly realized that the use of fossil groundwater—even in large reserves such as the Nubian aquifer—needs to be managed in a planned manner using different criteria than used for managing renewable groundwater. Virtual water imports, off-farm livelihoods, shifting and reduction in agricultural areas, wastewater treatment and reuse, desalination are elements of strategies used to ease pressure on fossil groundwater.

Type III: Wealth-creating GwSE's

In recent decades, groundwater has become increasingly important in meeting water needs of industries and industrial agriculture in many developed countries such as Spain, US, and Australia. Three key characteristics of Type III GwSE's are: (a) users are normally few, large and identifiable; as a result, it becomes possible to create and enforce rules, norms, rights and economic incentives to regulate use by creating a formal economy; (b) using groundwater as a factor of production, Type III GwSE's generate substantial wealth which is shared by relatively small number of resource users; and (c) as a result, these attract and support scientific and technical wherewithal for intensive management of the resource and its use.

Type IV: Livelihood supporting GwSE'

In terms of groundwater quantity and numbers of people involved, by far the largest growth in groundwater use has occurred in sustaining subsistence crop and livestock farming which are the mainstay of billions of poor people in developing agrarian economies around the world such as India, Bangladesh, Nepal, and China. (see Figure 2)[1]. Out of the global annual groundwater use of 950-1000 km^3, Type IV GwSE's likely accounts for half or more. From the resource governance viewpoint, these represent a different ballgame altogether because: (a) they are dominated by large diffuse masses of small users who are neither registered, nor licensed, operating as they do in totally informal irrigation economies untrammeled by laws and regulations; (b) unlike Type III GwSE's of Spain, US and Australia, Type IV GwSE's support large numbers of poor people but generate little wealth in absolute or relative terms[2]. A groundwater user in South Asia produces a gross output of

[1]The FAO estimates of groundwater irrigated area based on data provided by member governments are in my view gross underestimates for countries in South Asia. Even these under-estimates put into bold relief why sustainable groundwater use in agriculture has emerged as a key challenge in this region.

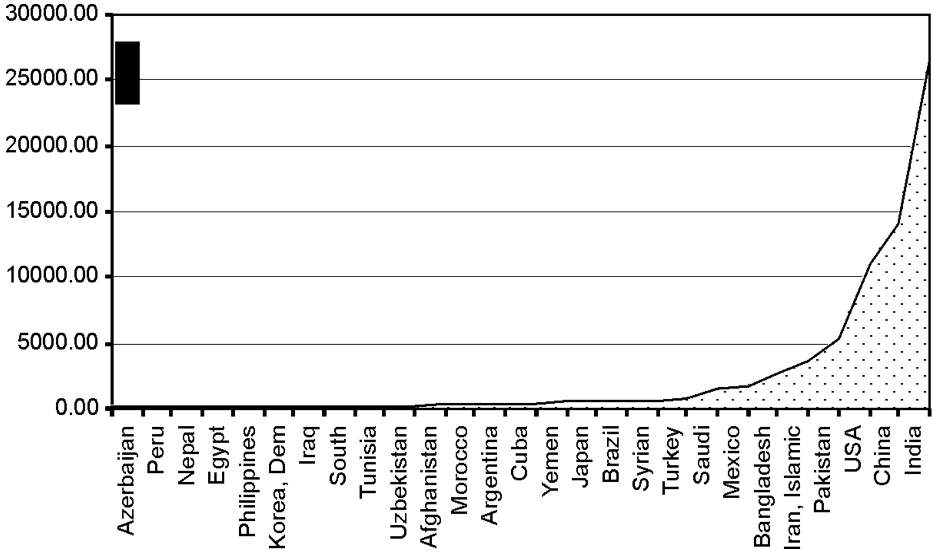

Figure 2. Groundwater irrigated area in countries with intensive groundwater use in agriculture (FAO Aquastat 2003 and other sources)

US $ 400/ha from irrigating crops; in contrast, a Spanish farmer in Andalusia region generates gross output/ha of US $ 8000/ha on average but can go up to US $ 75000 (Llamas 2003); (c) despite these apparently low returns, small holders in Type IV GwSE's have huge stakes in groundwater irrigation because it has served as one of the largest and most potent 'poverty reduction' programs (DebRoy and Shah 2003) in recent decades; (d) since science, technology and management tend to get attracted to wealth generation more easily than to poverty reduction, Type IV GwSE's attract far less of groundwater management inputs than Type III GwSE's[3].

Type V: GwSE's based on trans-boundary aquifers

Numerous aquifers in the world are shared by two or more sovereign states; most of these are small but some—like the Nubian with an estimated reserve of

[2]South Asia uses around 240-260 km³ of groundwater in agriculture annually providing supplemental irrigation to 60-75 m ha of grain, millet, pulse and fiber crops; however, the economic value of agricultural output this water supports is around US $ 35-40 billion because it is used largely for low value subsistence grain crops by peasants. Spain, in contrast, uses 4-5 km³ of groundwater for irrigating 1 million ha of mostly grapes for wineries, and fruit and flowers for export to EU; and its economic value is estimated by Martinez Cortina and Harnandez-Mora (2003) at 4.5-10.7 billion Euros, or at 0.8 Euro to a US dollar, US $ 5.6-13.4 billion!

[3]The resources available to groundwater organizations highlight the contrast. India uses 200 km³ of groundwater annually, which likely benefits 600 million rural people; but her Central Ground Water Board's annual budget is around US $ 31 million (http://indiabudget.nic.in). The US uses 110 km³ in agriculture, which likely supports a million farmers. However, the USGS budget for 2005 is nearly US $ 1 billion. Even allowing for Purchasing Power Parity, the differences in resources available to groundwater management agencies in the two types of groundwater socio-ecologies are evident (http://www.usgs.Gov/budget/2005/ 05budgetpr.html).

over 500,000 km^3—are huge (Puri and El Naser 2003). As intensive groundwater use emerges in these aquifers, their effective governance becomes subject to a new class of problems needing unique institutional responses and mediating mechanisms. Management of shared aquifers between Israel and Palestine, between the US and Mexico, and amongst countries of the Nile basin who will share the Nubian illustrate these unique issues. For the purposes of this paper, however, we will ignore Type V GwSE's, important as they are in the global groundwater setting.

Groundwater and Poverty in Asia

Globally, growth in groundwater irrigation has had little to do with the occurrence of the resource; if anything, led essentially by demand-pull, intensive development has tended to occur in arid and semi-arid regions with relatively poor groundwater endowments. Regions with abundant rainfall and recharge—much of South America, Canada, South East Asia, and Southern China-make little use of groundwater in agriculture. Intensive groundwater use, where extraction/km^3 of annual recharge is high, has also had little to do with the geology of regions[4]. Instead, Type IV GwSE's have: (a) high population density; (b) high livelihood dependence on peasant farming dominated by small, fragmented land holdings; (c) arid to semi-arid and often monsoon climate. Of the 300 million ha of irrigated land in the world, some 85-95 million depend on groundwater[5]; over 85% of these areas are in India, Pakistan, Bangladesh, Iran and North China plains. All these have all the three characteristics outlined above. Bangladesh, with high precipitation, is more like South East Asian countries; but its flood-proneness makes groundwater irrigation critical for improved agricultural productivity it needs to support its very high population density. As a result, from only a few thousand shallow tubewells in 1980, Bangladesh has added nearly a million since then, raising its groundwater irrigated area from close to nothing in 1980 to 2.8 million hectare in 2000, which is 90% of its cultivated land (BBS 2002). Figure 3, which overlays tubewell density (each black dot represents 5000 groundwater structures) over population density in India and Pakistan Punjab, shows that high tubewell densities follow high population density in Indo-Gangetic basin where the resource is abundant to southern India where resource is very limited. However, tubewell density is low in Central India where population density is low but untapped resource is available. This is

[4]In India, intensive groundwater use occurs in the Ganga basin, which has excellent alluvial aquifers with abundant recharge; but it also occurs in southern peninsular India dominated by hard rock aquifers with low storage coefficients, as suggested by Figure 3.

[5]These are author's estimates. FAO Aquastat (2003) estimates groundwater irrigated for Africa at 1.02 million ha, for Asia (excluding China) at 43.6 million ha, and North and Central America (excluding the USA) at 2.2 million ha (Burke, 2003). It also places total irrigated areas for member countries (excluding China and USA) at around 200 M ha. FAO Aquastat data for most countries are 6-10 years old. Moreover, FAO places groundwater-irrigated area in India at just 26 million ha; however, the net area irrigated by groundwater in India in 2004 is more like 55-60 million ha at the least. The Minor Irrigation Census carried out by Government of India in 1993-94 placed net groundwater irrigated area at 30.13 M ha 10 years ago (GoI 2001); and this census excluded Gujarat, Maharashtra, Karnataka and Tamilnadu, which represent huge Type IV GwSE's in India. All in all, I believe that in 2004, global irrigated area is more likely to be close to 300 than 200 M ha; and groundwater irrigated area in Asia is more like 85-90 M ha.

perhaps why Africa with its low population density will never experience the kind of groundwater irrigation explosion that South Asia has.

Type IV GwSEs of South Asia and North China plains represent a veritable anarchy functioning on a colossal scale. India, for instance, has been adding 0.8-1 million new tubewells every year since 1990; and there is no sign of deceleration in this trend. One in four of India's farmers have invested in irrigation wells; most of the remaining buy pump irrigation service from their tubewell-owning neighbors. Government of India claims 60% of India's irrigated areas are served by groundwater wells; independent surveys suggest the figure may well be 75%; and even more if conjunctive use areas are included. Much the same is true of Pakistan, Nepal *terai*, Bangladesh, and Hebei, Shandong, and Henan provinces in the Yellow river basin in North China plains. Governments and donors have invested heavily in building major dams and canal irrigation projects in these regions; but, as of now, by far the bulk of the irrigation—and livelihood benefits—are delivered by groundwater wells. Over half of the total populations of India, Pakistan and Bangladesh have a livelihood-stake in well irrigation. During 1970's, India discussed different strategies for irrigation command areas and for rain-fed farming regions. Thanks to groundwater development, there are hardly any rain-fed farming 'regions' or even villages in India; there are just rain-fed and mostly groundwater irrigated plots.

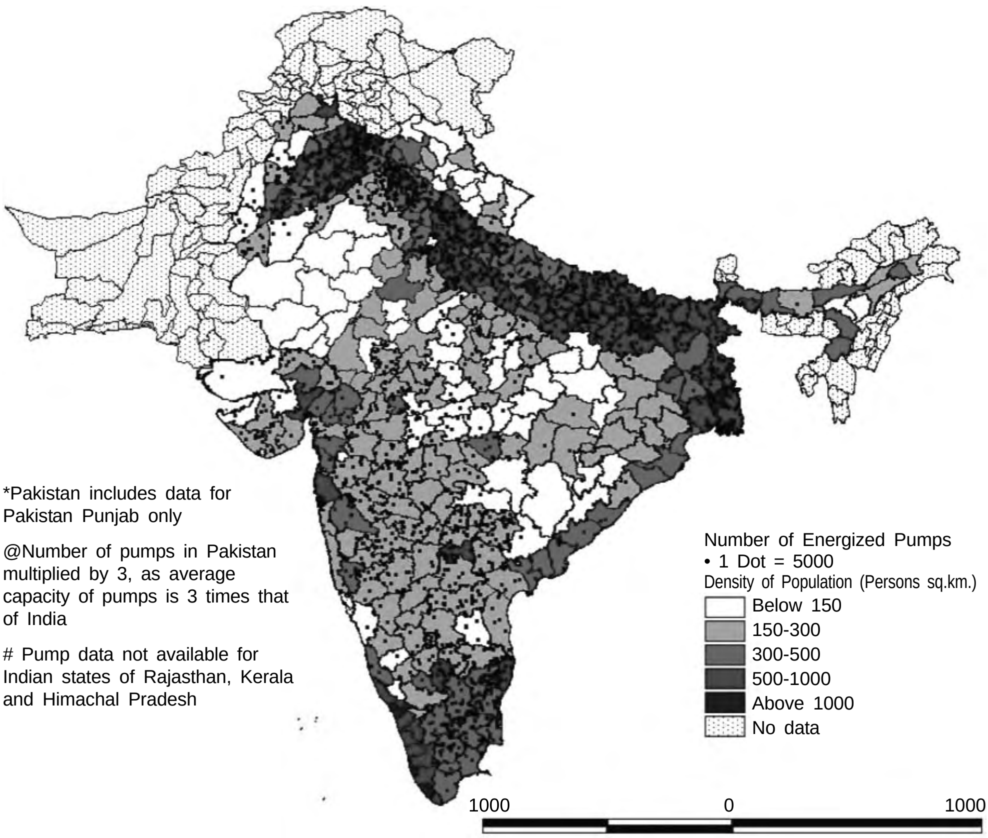

Figure 3. Density of population and distribution of energized pumps in India and Pakistan

Groundwater Governance: Institutions, Laws and Policies

This runaway growth in Type IV GwSE's in developing countries in Asia exemplifies best how poverty works as the enemy of environment. High population pressure on agriculture has induced farmers to overwork their tiny land holdings in search of more livelihoods per unit of all that land has to offer—soil nutrients, moisture and underlying groundwater. Widespread indications of groundwater depletion and deterioration, rising energy use and pumping costs, well failures, weakening drought-protection suggest that the 'groundwater boom', which has done more to sustain the poor than all poverty eradication programs, will burst, sooner or later. There are also environmental repercussions in the form of drying up of wetlands and streams, reduced lean season flows of rivers, and salinity ingress in coastal areas. Groundwater quality issues too have assumed serious proportions in many parts of the world; irrigating with saline groundwater, as in the Indus basin and in Australia, have raised the specter of soil salinization on large areas. People and policy makers in many parts of the world—but especially in South Asia and North China Plain- are waking up to the dangers of drinking poor quality groundwater high in arsenic or fluoride or other contaminants.

Effective management of groundwater demand to match available recharge is considered central to sustaining intensive groundwater use in Type IV GwSE's; and strategies recommended to them are those that have been tried out in Type II and III GwSE's. Community management of groundwater as a common property resource is widely espoused to South Asian policy makers based, for example, on the experience of countries like Spain and Mexico. The issue is if such models can or should be transplanted without ascertaining their effectiveness on their home turf. Spain's 1985 Water Law mandated Water User Associations at aquifer level; but of some 1400 that were registered, Martinez-Cortina and Hernandez-Mora (2003) could identify "only 2 which have actively managed their aquifers, financing all their activities from membership fees" (p.318). One reason why these failed, as Llamas points out, was that these users associations mandated top-down by law have been 'fraught with strong resistance from farmers' (Llamas 2003). Mexico likewise has been experimenting with COTAS (Technical Committee for Aquifer Management); these too are yet to begin playing effective role in aquifer management (Shah, Scott and Bucheler,2004). Groundwater districts of US are often held out as a model in community groundwater management; however, the US experience itself is a mixed bag. Since 1949, Texas allowed the creation of Underground Water Conservation Districts (UWCDs) with discretionary power to regulate groundwater withdrawals and space wells as well as their production. However, Smith (2003:264-265) notes, "Although over forty UWCDs have been created in Texas, they have not been effective managers of groundwater." and further that "..creating groundwater districts is not—in and of itself—going to ensure sound groundwater management."

Demand restriction has also been tried through a combination of pricing, legislative and regulatory action, licensing and permits, and by specifying property rights. Direct regulation worked better in countries with a hard state, as in Iran, which imposed an effective ban on new tubewells in 1/3rd of its central plains, or Russia which has banned the use of groundwater for irrigation to protect it for domestic uses (Igor.S Zektser, pers. Comm.). However, bans proved counter-productive in Mexico, which has issued 14 bans on new tubewells since 1948; however, "every announcement of an imminent ban stimulated a flurry of tubewell making activity" (Shah, Scott and Buecheler, 2004). Mexico has also tried, in early 1990's, creating tradable private property rights in groundwater by issuing 'concessions' to tubewell owners with pre-specified volumes of groundwater to be pumped every year. The idea was that once private water rights are created, users would have strong incentive in protecting the resource, especially if such rights were valuable and tradable (Holden and Tobani 2001). Concessions have led to registration of tubewells, useful in itself; but enforcing the groundwater quota has proved administratively impossible even though Mexico has all of 90,000 irrigation tubewells, compared to North China's 4.5 million and India's 20 million. China's water withdrawal permits system and withdrawal fees have not helped reduce agricultural withdrawal although it has helped control urban groundwater depletion somewhat. Saudi Arabia has begun controlling groundwater irrigation by paying farmers for supplying water to towns (Abderrahman, 2004. Pers. Comm.).

In transposing the lessons from Mexico, Spain, western US experiments to Asian contexts, several issues come up: (a) there is no evidence that these experiments have actually led to effective resource governance in Mexico, Spain or the US; western US has been struggling with groundwater governance for over 50 years now; and yet horror stories of groundwater abuse in the US galore (for a recent one, see, Glennon's book "Water Follies" reviewed by Jehl 2002); (b) groundwater demand restriction has normally worked only when alternative supplies are arranged; thus many cities in North China have been able to crowd out private urban tubewells but only after importing surface water and providing it in lieu of pumping groundwater. Similarly, 50 years after it began depleting its groundwater, Arizona could control groundwater demand only by providing farmers subsidized Colorado River water in lieu of pumping groundwater. (Jacobs and Holway, 2004:58). Spain's 2001 National Water Plan's response to groundwater depletion on its southeastern Mediterranean coast is importing surface water from Ebro river basin (Martinez Cortina and Hernandez-Mora, 2003). In effect, then, what has commonly worked is not demand management, but 'groundwater substitution' with imported water; (c) finally, the socio-economic context of Type III and Type IV GwSE's are so vastly different, that copycat transfer of lessons from former to later would be bound to fail as can be inferred from Table 1. The US has small number of large capacity pumping plants that produce 110 km^3 of groundwater for

Table 1. Structure of national groundwater economies of selected countries

Country	Annual ground -water use (km^3)	No of ground-water structures (million)	Extraction/ structure (m^3/year)	% of population dependent on groundwater
India	185-200	20.0	9000-10000	55-60
Pakistan	45	0.5	90000	60-65
China	75	3.5	21500	22-25
Iran	29	0.5	58000	12-18
Mexico	29	0.07	414285	5-6
USA	110	0.2	550,000	<1-2

a wealth-generating irrigation machine on which less than 2% of Americans depend for their livelihood. India, in contrast, has around 20 million small pumps scattered over a vast countryside, each pumping on average 10,000 m^3 to irrigate their tiny parcels in a peasant economy that has 55-60 percent of Indians as direct or indirect stake holders. Here, resource management capacities are poor. Regulatory agencies are skeletal and the numbers of tiny users to be regulated huge and scattered over a vast countryside. Then, because groundwater irrigation is central to their livelihoods, farmers organize readily—and often violently—to oppose any effort that hits their irrigation economy. Above all, many environmental ill effects of intensive groundwater use begin to occur at low levels of groundwater development. Drying up of wetlands, reduction in summer low flows in rivers and streams, increased fluoride levels in groundwater are examples. Reversing all these would require restoring pre-development conditions by cutting the present rate of groundwater use by 70 percent or more in many regions. Even if possible, doing this would throw out of gear millions of rural livelihoods and cause massive social unrest.

Context Specific Strategies: The Case of India

This is why people, agencies and leaders in Type IV GwSE's are often lukewarm to 'groundwater demand restriction' approaches even as concerns about resource protection and sustainability are mounting. While learning intelligently from the experiences of Type II and III GwSEs, Type IV socio-ecologies need to build their homegrown approaches that strike a balance between the need to protect the resource and support their poor people. India exemplifies this challenge in its most serious form. It is facing unsustainable groundwater use in western unconfined alluvial aquifers, very much like the North China plains, as well as in peninsular hard-rock India where aquifers have little storage but precipitation is relatively better. Three large-scale responses to groundwater depletion in India have emerged in recent years in an uncoordinated manner, and each presents an element of what might be its coherent strategy of resource governance:

(i) *Energy-irrigation nexus:* Throughout South Asia, the 'groundwater boom' was fired during the 1970's and 80's by government support to tubewells and subsidies to electricity supplied by state-owned electricity utilities to farmers. The invidious energy-irrigation nexus that emerged as a result and wrecked the electricity utilities and encouraged waste of groundwater are widely criticized. However, hidden in this nexus is a unique opportunity for groundwater managers to influence the working of the colossal anarchy that is India's groundwater socio-ecology. Even while subsidizing electricity, many state governments have begun restricting power supply to agriculture to cut their losses. Much IWMI research has shown that with intelligent management of power supply to agriculture, energy-irrigation nexus can be a powerful tool for groundwater demand management in Type IV socio-ecologies (Shah et al, 2003b). IWMI research has also shown that after all its labors to create tradable property rights in groundwater and creating COTAS, Mexico has finally had to turn to electricity supply management to enforce its groundwater concessions (Scott, Shah and Buechler 2003).

(ii) *Inter-basin transfers to recharge unconfined alluvial aquifers:* In western India's unconfined alluvial aquifers, it is being increasingly realized that groundwater depletion can be countered only by importing surface water, Arizona-style. Jiangsu province in eastern China has implemented its own little inter-basin water transfer from Yangzee to counter groundwater depletion in the northern part. Similarly, one of the major uses Gujarat has found for the water of the by now famous Sardar Sarovar Project (SSP) on Narmada river is to recharge the depleted aquifers of north Gujarat, and Kachchh. A key consideration behind India's proposed mega-scheme to link its northern rivers with peninsular rivers too is to counter groundwater depletion in western and southern India.

(iii) *Mass-based recharge movement:* In many parts of hard-rock India, groundwater depletion has invoked wildfire community-based mass movement for rainwater harvesting and recharge, which interestingly has failed to take off in unconfined alluvial aquifers. It is difficult to assess the social value of this movement partly because 'formal hydrology' and 'popular hydrology' have failed to find a meeting ground. Scientists want check dams sited near recharge zones; villagers want them close to their wells. Scientists recommend recharge tubewells to counter the silt layer impeding recharge; farmers just direct floodwaters into their wells after filtering. Scientists worry about upstream-downstream externalities; farmers say everyone lives downstream. Scientists say the hard-rock aquifers have too little storage to justify the prolific growth in recharge structures; people say a recharge structure is worthwhile if their wells provide even 1000 m^3 of life-saving irrigation/ha in times of delayed rain. Hydrologists keep writing the obituary of the recharge movement; but the movement has spread from eastern Rajasthan to Gujarat, thence to Madhya Pradesh and Andhra Pradesh. Protagonists think—as caricatured in Figure 4- that with better planning of recharge structures and larger coverage, decentralized recharge movement can be a major response to India's groundwater depletion because it can ensure that water tables in pockets of intensive use rebound close to pre-development levels at the end of the monsoon season every year they have a good monsoon, which is at least twice in 5 years. They surmise that this is not impossible because even today, India's total groundwater extraction is barely 5% of its annual precipitation.

An important aside to India's groundwater story is that it has emerged as a truly people's GwSE. Indian governments at centre and state levels have been trying for decades to secure people's participation in improving the management of canal systems, water supply and sanitation systems, drainage systems and so on, but to little avail. As a result, under remote, bureaucratic management, public water infrastructure and services have steadily deteriorated. The groundwater economy, in contrast, has never suffered for want of people's participation. What it has lacked is appropriate and intelligent participation from public agencies, science institutions and the international community. Indian engineers take pride in having built some of the finest dams in the world; but India is yet to see large-scale initiatives in ASR (Aquifer Storage and Recovery) as in New South Wales, or learn to operate major groundwater banking operations as in Arizona, or master the art of depleting and refilling aquifers on an annual basis as the French do with the Montpiller aquifer

Considered from this perspective, one can stand India's groundwater problem on its head; and argue that the emergence of intensive groundwater use in regions with 1000-1400 mm normal rainfall may well be a great hidden opportunity. Through their 20 million tube wells, India's farmers have created a 185-200 km^3 reservoir—in the form of dewatered aquifers-which can regularly collect, store and deliver at the users' door-step a relatively high quality water service that in some ways is 'self-regulating and self-financing'. Like all surface reservoirs, the underground reservoir has limitations; but this is precisely why science and management are required. Using this opportunity would require investing in creating scientific capability and infrastructure for groundwater recharge a top priority for Type IV GwSE's such as India and Bangladesh with significant renewable water resources. Hundred years ago, when India did not use much groundwater and the tubewell-pump-recharge technologies were not available, it was understandable for the colonial government to concentrate resources on building great canal irrigation systems. But today—when wells, pumps and recharge structures are the dominant choice of millions of India's small holders, within and outside canal commands—a smart water policy might focus on devoting resources to supporting this people's GwSE rather than throwing good money after bad, as

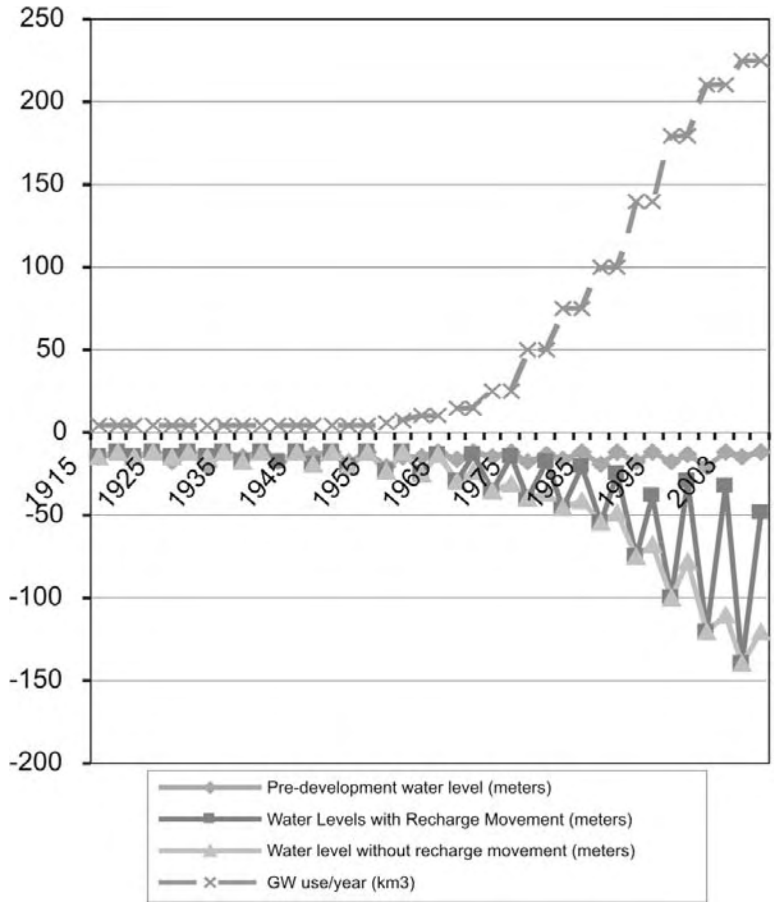

Figure 4. Farmers' perception of potential impact of decentralized recharge movement in India

India is intent on doing, in pursuing an irrigation development strategy based on canal irrigation that has left a great deal to be desired.

Summary and Conclusion

If the world's water crisis is "mainly a crisis of governance" (GWP, 2000), groundwater represents the grimmest side of this crisis in Asia. The Australian Groundwater School at Adelaide is apt in its credo, which says, "Groundwater will be the enduring gauge of this generation's intelligence in water and land management". In exploring the nature of the global groundwater challenge, this paper has (a) highlighted the tremendous contribution groundwater has made to human welfare globally; (b) analyzed socio-ecological implications of runaway growth of groundwater irrigation, especially in some Asian countries; and (c) argued why groundwater governance strategies must be context-specific to be effective.

Type IV GwSE's—where protecting the resource is often in direct and immediate conflict with livelihood support to rural poor—presents the most complex resource governance challenge facing the world's water professionals. Groundwater managers in Type IV GwSE's need to learn intelligently from approaches tried in Type II and III GwSE's, which have been evolving, refined structures of groundwater governance through demand and supply side management. Their challenge, however, is to fit these approaches into the unique contextual realities of Type IV GwSE's.

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Groundwater Resources Development in Bangladesh: Contribution to Irrigation for Food Security and Constraints to Sustainability

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Abstract

Bangladesh occupies the major part of the delta of the Ganges-Brahmaputra-Meghna (GBM) river system and lies mostly within the Bengal Basin. The unconsolidated near surface Pleistocene to Recent fluvial and estuarine sediments underlie most of Bangladesh, generally form prolific aquifers, and groundwater is drawn predominantly from these quaternary strata. Since the 1960's, groundwater has been used extensively as the main source of drinking and irrigation water supply. About 75 percent of cultivated land is irrigated by groundwater and the remaining 25 percent by surface water. Of the abstracted groundwater about 70-90 percent is used for agricultural purposes and the rest for drinking and other water supplies. The country started emphasizing groundwater irrigation in mid-seventies with deep tube wells (DTW), but soon shifted its priority to shallow tube wells (STW).

The groundwater resource is one of the key factors in making the country self sufficient in food production. Groundwater-irrigated agriculture plays an important role in poverty alleviation and has greatly increased food production. The need for conjunctive use of surface and groundwater is highlighted in the National Water Policy (NWPo, 1999). This policy has established a linkage between water resources and the rural livelihood and ultimately the link to poverty alleviation. The country's GDP is highly dependent on the development of water resources in general. Trends indicate that farmers are becoming increasingly productive as a result of enhanced access to irrigation through groundwater (BMDA, 2000). For groundwater irrigation, the prime source of power energy for lifting water is fossil fuel (diesel or petrol) and electricity. Hence the linkage between the energy for lifting groundwater and irrigation economics is also very important.

Until now, availability of groundwater has not been a constraint to agricultural development. But this resource is increasingly facing various problems including quality hazards in many areas where the exposure to pollution from agriculture, urbanized areas and industrial sites as well as arsenic contamination in shallower groundwater aquifers makes the water unfit for human consumption and in some cases even for irrigation purposes. High rates of pumping for irrigation and other uses from the shallow aquifers in coastal areas may result in widespread saltwater intrusion, downward leakage of arsenic concentrations and the general degradation of water resources. Besides, use of agrochemicals *may cause contamination of shallow groundwater and sediments. Continuous decline of groundwater tables due to over-withdrawal has also been reported from some areas. Thus the overall situation calls for urgent groundwater management for sustainable development. Groundwater management must adopt an integrated approach taking into account a wide range of ecological, socio-economic and scientific factors and needs.*

Introduction

The Ganges-Brahmaputra-Meghna river system has the largest total sediment load in the world, eroded from the Himalayas and generating fluvio-deltaic sediment layers, which form productive fresh water aquifers in most parts of Bangladesh. The country has gained a significant success in the development of groundwater for its irrigated agriculture and rural water supply. The country started emphasizing groundwater irrigation in the mid-seventies with deep tube wells (DTW), but soon shifted its priority to shallow tube wells (STW). The growth of minor irrigation flourished just after the independence of 1971. Until 1950's farmers used only traditional means of irrigation, the swing basket and '*doan*'. These traditional technologies are capable of lifting water up to about 1 to 1.5m. The first major irrigation project started in the early sixties in the Thakurgaon area, northwest of Bangladesh under Bangladesh Water Development Board (BWDB) sinking 380 DTWs. Increasing demand due to the growth of population made it necessary to increase food production. DTW and STW irrigation was extended rapidly during the late 1970's and the 1980's. As a result the target for self-sufficiency in food has almost been achieved. Minor irrigation using groundwater has, in fact, been the single most important driving force behind the steady expansion of agricultural output in recent years. Besides STW and DTW, the minor irrigation also involves pumping technologies like deep set/ very deep set shallow tube wells (DSSTW/ VDSSTW), force mode tube wells (FMTW) and low lift pumps (LLP), etc. DTWs are cased wells where pump is set within the well below the water level. A diesel engine or an electric motor is mounted above the well and is connected to the pump by shaft. STWs are irrigation wells fitted with a suction mode centrifugal pump and a small diameter well to depths of 4 to 6 m. Diesel engines or electrical motors coupled with centrifugal pumps are placed at the wellhead and the casing itself acts as a suction line. DSSTWs and VDSSTWs are set into a pit of about 2m where water table decline below suction capacity of 7-8m. LLPs are significant for surface water irrigation mounted on a floating platform. The pumping capacities of STW, DTW and LLP are around 12,000; 50,000 and 12,000-50,000 m^3/day, respectively. However, the majority of the technologies are STW and LLP. STW has increased in numbers throughout the country from 133,800 in 1985 to 925,200 in 2004 (Table 1). There were 24,700 DTWs in operation in 2004. In the minor irrigation sector, based on both groundwater as well as surface water, groundwater is likely to continue to be the main source of irrigation expansion and a key contributor to future agricultural growth.

STWs are driven by surface mounted centrifugal pumps, which can draw water from up to 7.5m depths. These are relatively inexpensive, easy to install, easy to maintain and are shared between small groups of farmers. With the continuous abstraction, the water table in many areas started declining and the STWs were no

Table 1. Groundwater development by STW[1] and DTW[2] (BADC, 2005)

Year	No. of STW	No. of DTW	Year	No. of STW	No. of DTW
1985	133,800	15,300	1993	348,900	25,700
1988	186,400	23,500	1995	488,900	26,700
1989	217,900	23,300	1996	556,400	27,200
1991	270,300	21,500	1998	664,700	25,400
1992	309,300	25,500	2001	707,600	23,500
			2004	925,152	24,718

[1] STW = Shallow Tubewell, [2]DTW = Deep Tubewell

more capable of pumping under suction mode during the peak irrigation period.

The development of groundwater for irrigation has had a major positive impact on food grain production in Bangladesh. Hence, groundwater irrigated agriculture plays an important role in poverty alleviation. However, excessive groundwater abstraction for irrigation has posed a great challenge to the rural drinking water supply using hand-operated tube wells. The presence of arsenic has further worsened the situation. In urban and peri-urban areas, groundwater abstraction has lowered water levels beyond the potential of natural recharge. Thus the overall situation calls for an urgent groundwater management and sustainable development. Statistics reveal that about 75 percent of total cultivated land is irrigated by groundwater and 25 percent by surface water (Table 2).

Table 2. Status of irrigation in Bangladesh, 1995-1996 (WARPO, 2001)

Mode of irrigation	Type of equipment	No. of equipment in operation	Area irrigated ha	%
Groundwater	STW	556,400	1,937,700	57
	DSSTW[1]	19,300	64,600	2
	DTW	27,200	537,900	16
Surface Water	LLP[2]	60,700	577,200	17
	TRAD[3]	673,000	226,400	7
Others		161,800	50,100	1
Total			3,394,900	100

[1]DSSTW = Deep set shallow tubewell, LLP = Low lift pump TRAD = Treadle pump.

For groundwater irrigation, the prime source of power energy for lifting water is fossil fuel (diesel or petrol) and electricity. Both sources of power/energy are costly for the rural people. However, irrigation has direct impact on food and livelihood security. Hence, in the context of energy sector instruments (reform/ restructuring of energy sector, pricing of power, reliability of supply) the linkage between the energy and irrigation economics is very important.

National Water Policy and Groundwater

The purpose of all water resources-based policies and those associated with water resources such as agriculture, fisheries and environment is to allocate resources and allow the development in such a way as to maximise the benefits to the population and enhancing the resources itself for a sustainable development. The need of conjunctive use of surface and groundwater is highlighted in the GoB's National Water Policy (NWPo) formulated in 1999. The NWPo has provided broad principles of development of water resources and their rational utilization under different constraints. It is the policy to ensure that all necessary means and measures will be taken to manage the water resources of the country in a comprehensive, integrated and equitable manner. This policy has established a linkage between the water resources and the rural livelihood and ultimately to poverty alleviation.

To address issues related to harnessing and development of groundwater and the general management of water resources in an efficient and equitable manner the following objectives are highlighted in the NWPo,

- Develop a state of knowledge and capability that will enable the country to design future water resources management plans by itself addressing economic efficiency, gender equity, social justice and environmental awareness to facilitate achievement of the water management objectives through broad public participation.
- Improve efficiency of resource utilization through conjunctive use of all forms of surface water and groundwater for irrigation and water supply. Develop and disseminate appropriate technologies for conjunctive use of rainwater, groundwater and surface water.
- Strengthen appropriate monitoring organizations for tracking groundwater recharge, surface and groundwater use and changes in surface and groundwater quality. Preserve natural depressions and water bodies in major urban areas for recharge of underground aquifers. Take steps to protect the water quality and ensure efficiency of its use.
- Encourage future groundwater development for irrigation through both the public and private sectors, subject to regulations that may be prescribed by government from time to time.

The NWPo also emphasizes collaboration with co-riparian countries to establish a system for exchange of information and data on relevant aspects of hydrology, morphology, water pollution, ecology, changing watershed characteristics, cyclones, droughts, flood warning etc. and to help each other understand the current and emerging problems in the management of the shared water resources as well as to seek international and regional cooperation for education, training, and research in water management.

The government reserves the right to allocate water to ensure equitable distribution, efficient development and use and to address poverty. The policy is to continue with irrigation expansion with tube wells and hand-operated tube wells will be gradually replaced by force mode '*Tara*' pumps with increased lift. Fresh drinking water is pumped from deeper layers in the salinity-prone southern part using force mode deep wells. Cities and urban areas are facing the problem of receding water table due to heavy groundwater extraction for piped water supply. Dhaka city experiences a declining water level at the rate of 1 to more than 1.5 m each year. In the wake of abstraction beyond natural recharge potential, the policy is to gradually shift emphasis from groundwater-based water supply towards surface water based water supply around the city area.

Groundwater Aquifers in Bangladesh

Generally, four major physiographic units exist at the surface of Bangladesh (Figure 1). These are, (a) Tertiary sediments in the northern and eastern hills; (b) Pleistocene Terraces in the Madhupur and Barind Tracts; (c) Recent (Holocene) floodplains of the Ganges, the Brahmaputra and the Meghna rivers and (d) the Delta covering the rest of the country. Most of the present land surface of the country covered by the Holocene flood plains deposited by the GBM river systems. About 6000 year ago sea level was much lower and the major rivers dissected deep channels adjacent to the Madhupur and Barind Tract areas. Deltaic floodplains with some Pleistocene terraces constitute the major part of the Basin. Basinal sediments consist primarily of unconsolidated alluvial and deltaic deposits except the complex geology area of pre-quaternary sediments that cover the northeastern and southeastern hilly areas of the country. Together with the tertiary sedimentary sequences the maximum thickness of the deposit is more than 20km.

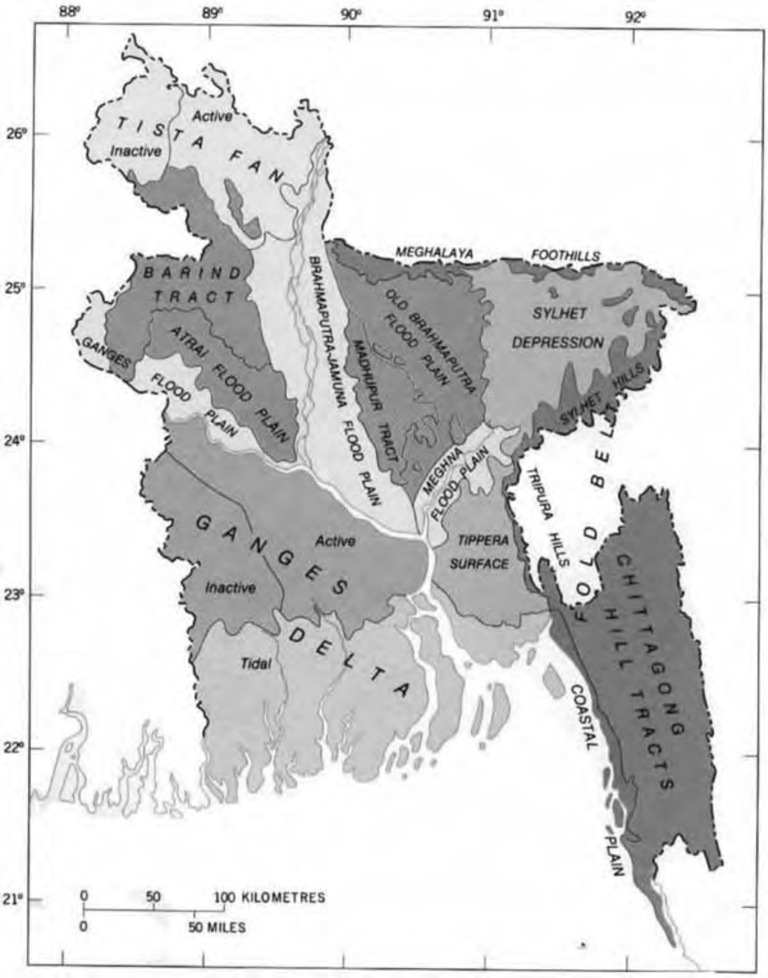

Figure 1. Phygiographic map of Bangladesh (Alam et al, 1991)

The tropical monsoon climate together with favorable geological and hydrogeologic conditions indicates high potential storage of groundwater in the country. The unconsolidated near surface Pleistocene to Recent fluvial and estuarine sediments underlying most of Bangladesh generally form prolific aquifers. Thick semi-consolidated to unconsolidated fluvio-deltaic sediments of Miocene age to the recent form many aquifers. But except the Dupi Tila sandstone formation of the Plio-Pleistocene age, others are too deep to consider for groundwater extraction except in the hilly region (18 percent of Bangladesh). Most of the groundwater withdrawn for domestic or agricultural purposes in the Barind and Madhupur uplands areas is from the Dupi Tila aquifers. The floodplains of the major rivers and the active/inactive delta plain of the GBM Delta Complex occupy 82 percent of the country. From the available subsurface geological information it appears that most of the good aquifers occur between 30 to 130 m depth. These sediments are cyclic deposits of mostly medium to fine sand, silt and clay. The individual layers cannot be traced for long distances, horizontally or vertically.

On a regional basis, three aquifers have been identified and named by BWDB-UNDP (1982) (Figure 2). These are,

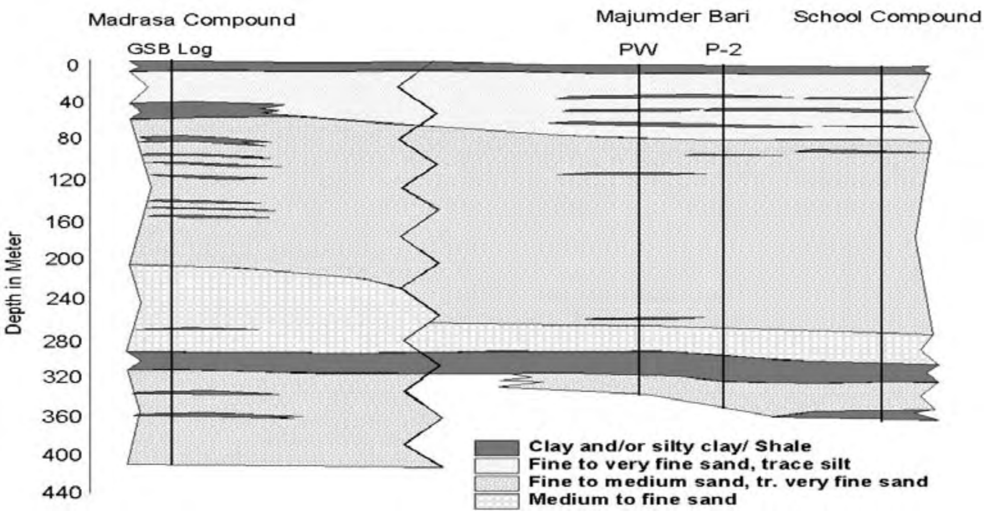

Figure 2. Aquifer system in lower delta floodplain, Sreerampur, Chandpur (BWDB, 2004)

The Upper (Shallow) or the Composite Aquifer

Below the surface clay and silt unit, less than few to several hundred meters thick very fine to fine sand, in places inter bedded or mixed with medium sand of very thin layers are commonly encountered. The thickness of this zone ranges from a few meters in the northwest to maximum of 60m in the south. Over most of the country it represents the upper water-bearing zone.

The Main Aquifer

The main water-bearing zone occurs at depths ranging from less than 5m in the northwest to more than 75m in the south and most of the country. It is either semi-confined or leaky or consists of stratified interconnected, unconfined water bearing formations. This aquifer comprises medium and coarse-grained sandy sediments, in places inter-bedded with gravel. These sediments occur to depths of about 140m below ground surface. Presently, groundwater is drawn predominantly from these strata.

The Deeper Aquifer

The deeper water-bearing unit is separated from the overlying main aquifer by one or more clay layers of varied thickness. Deep aquifers generally include those aquifers whose waters have no access vertically upward and downward but flow very slowly along the dips and slopes of the aquifers. The depths of the deep aquifers in Bangladesh containing usable water range from 190 to 960 m on the Dinajpur platform and 250 to 1500 m in the basin and mainly include the sediments of the Gondwana, Jaintia, Surma and Tipam groups and parts of the Dupi Tila Sandstone Formation (Khan, 1991). This water bearing-zone comprises medium to coarse sand in places inter-bedded with fine sand, silt and clay. At present the water-bearing formation deeper than 150-200 m are being exploited on limited basis in the coastal zone to cater to the need of municipal water supply and in the rural areas for drinking purpose. Large scale extraction has not been encouraged due to possibility of seawater intrusion or leakage of saline or arsenic contaminated water from the upper aquifer.

Considering age, except the hilly regions, aquifers can be divided into following two categories for floodplains, delta and terrace areas.

The Pleistocene Aquifers

The major terrace areas considered being of Pleistocene age of highly oxidized sediments including the Madhupur Tract in greater Dhaka, Tangail and Mymensingh districts and the Barind Tract in greater Rajshahi and Bogra districts. The Plio-Pleistocene aquifers of the Dupi Tila Formation lie beneath the Pleistocene Madhupur Clay Formation (Figure 3). This aquifer is composed of light grey to yellowish brown, medium to coarse sand with pebble beds and dated as about or more than

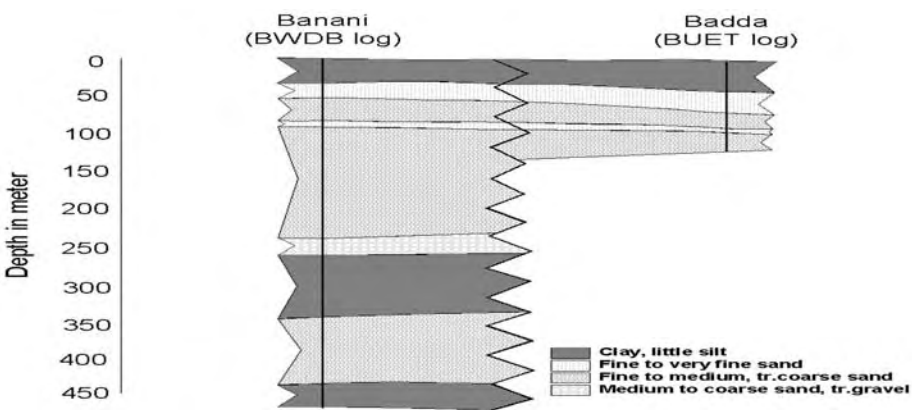

Figure 3. Pleistocene Dupi Tila aquifer of Dhaka city (Zahid et al, 2004)

20,000 years old (Aggarwal et al., 2000). All of the water for Dhaka city is withdrawn from this aquifer and the water is as yet arsenic safe.

This aquifer is confined to semi-confined in nature. The reddish-brown mottled deposits underlain by lower Pleistocene Dupi Tila Formation are more compacted and weathered and generally have a higher content of clay and silt than the recent Holocene alluvial deposits. The Dupi Tila forms the main aquifer beneath the terrace areas. Madhupur clay has been buried by younger sediments only on the margins where it lies beneath floodplain deposits (BWDB-UNDP, 1982).

With the existing deep tube well records in and around Manikganj district, two alluvial aquifer systems named Madhupur aquifer (Figure 4) and Jamuna aquifer are classified (Davies, 1994). The older Madhupur aquifer occurs within Dupi Tila Formation sediments that underlie the Madhupur Pleistocene terraces. The younger Jamuna aquifer system occurs within grey non-indurated alluvial sediments of the Dhamrai Formation that infill the Jamuna, Brahmaputra and Ganges river valleys. The Jamuna aquifer system occurs within non-indurated grey alluvial sands and gravels at the Late Quaternary Dhamrai Formation. The Lower Dhamrai Formation is fining upward succession of coarse sand and gravels deposited by strongly flowing braided rivers and were deposited between 20,000 and 48,000 year BP. The upper Dhamrai Formation with coarse to medium sands of maximum 7000year BP age were also deposited as a series of upward fining units, from smaller braided and meandering rivers.

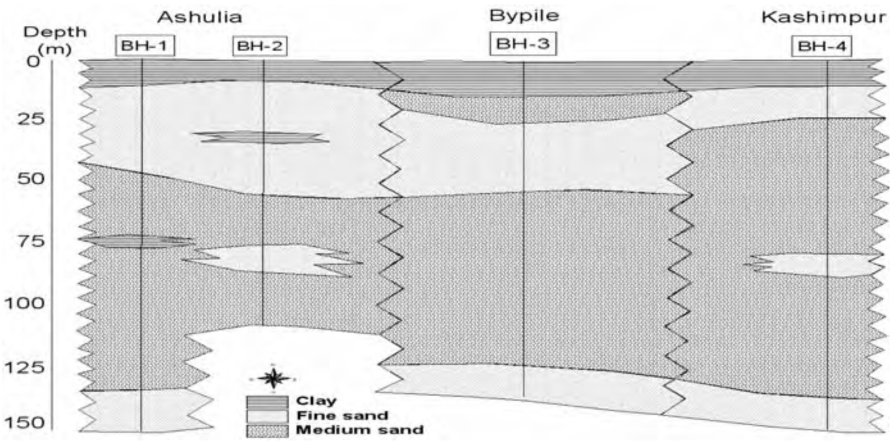

Figure 4. Madhupur Dupi Tila aquifer adjacent to Jamuna aquifer in Savar-Gazipur area ([a]Zahid et al, 2004)

Monsur (1990) dated the Dupi Tila Formation as being more than 900,000yrs old. The Dupi Tila sandstone forms the saturated zone on the Dinajpur shield and platform (Figure 5). This Dupi Tila Sandstone Formation extends all over Bangladesh probably excepting the western two third of the delta. The total thickness of the aquifers measures more than 300 m.

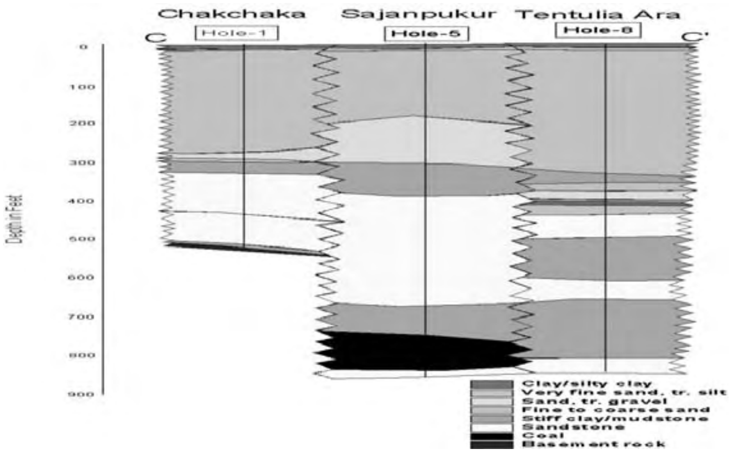

Figure 5. Sandstones reserve water in Platform area

The Holocene Aquifers

Other than the terrace areas, the remaining part of the Bengal Basin consists predominantly of Holocene alluvial and deltaic sediments. The age of Holocene aquifers range from 100 to more than 3,000 years (Aggarwal et al., 2000). In the land above tidal inundation, these deposits are composed primarily of silt and sand of appreciable thickness extending to depth of more than hundred meters. In the lower delta, they are principally silt, clay and peat. These sediments contain high water content and are generally loosely compacted and usually grey in color. Holocene and Pleistocene alluvium form the principal aquifers in the country.

The Recent alluvium deposits are of varying characteristics classified from piedmont deposits near the foot of the mountains to inter-stream alluvium including deposits in the interior, merging with swamp and deltaic deposits approaching the southern shoreline. Stratified deposits of sand, silt and clay constitute the subsurface formations. The character of the deposits varies remarkably vertically. Coarse and medium sand with gravel are found mainly in the northern border areas of greater Rangpur and Dinajpur districts. The sediments of coastal areas and northwestern part of Rajshahi district are predominantly silt, clay and fine sand with occasional coarse sand. The deeper aquifer consisting of fine to medium sand vertically extends 180 to more than 250 m depths from the surface and is separated by 10 to 50 m thick clay layer from the overlying aquifer (Figure 6) and is promising for groundwater exploration in Chittagong coastal plain aquifer (Zahid et al., 2004).

Rainwater is the principal source of groundwater recharge in Bangladesh. Floodwater, which overflows the river and stream banks, also infiltrates into the groundwater. Water from permanent water bodies (rivers, canals, wetlands, ponds, irrigated fields etc.) that lie above the water table also percolates to the groundwater. In the Pleistocene terraces, the recharge occurs through the incised antecedent drainage channels that cut through near-surface clays into the underlying sands. The greatest scope of recharge is within the coarse grained sediments and the least is within the fine-grained sediments like clay. The regional hydraulic gradient is low, reflecting the low topographic gradient. The groundwater flows generally

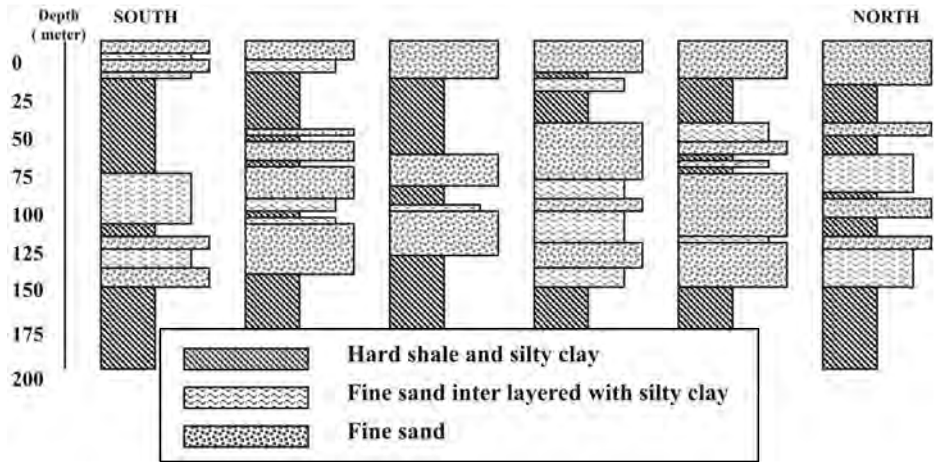

Figure 6. Rangadia coastal plain aquifer, Chittagong (Zahid et al., 2004)

from north to south. Most of the flow probably takes place through the in-filled incised channels under the major rivers.

Groundwater Irrigation and Poverty Alleviation

GDP in Bangladesh is highly dependent on the development of water resources in general. Trends indicate that smallholder farmers are becoming increasingly productive as a result of enhanced access to irrigation through groundwater. In terms of poverty alleviation, the small and marginal landholders are the primary target group for the National Water Management Plan (NWMP) when it comes to improving access to irrigation, enhancing their productivity, cropping intensities and the volume of agricultural products. For various social and economic reasons, these small and marginal farmers have been unable to increase production sufficiently, and consequently have been targeted as the focal points for development assistance.

To improve the quality of life of the people in the Barind area as well as to support and sustain agricultural growth, and improving the environmental situation the Barind Integrated Area Development Project (BIADP) (BMDA, 2000) has been under taken since 1986 covering 767,900 ha gross area of three Barind districts-Rajshahi, Nawabganj and Noagaon (40 percent of total). It is estimated that 62 percent of total cultivable area are irrigable utilizing groundwater. Before the project, Barind Tract was an unfavorable agricultural section of the country. With the increased and assured availability of irrigation water, the agricultural scenario has fundamentally changed. Most irrigation development in the project area has taken place through the use of DTWs and STWs. In all the Barind districts, the increase in number of DTWs has been manifested in the overall agricultural growth. The increase in yield of *Boro* rice is 43 to 120 per cent in the districts within the project area. A contributing factor to the spread in cultivation of modern rice varieties is the increased availability of irrigation water. According to the farmers, they would not have achieved in two decades what they have achieved in the last few years due to BMDA interventions. Cropping intensity in the project area increased from 141 percent in 1991 to 200 percent in 1998-99. At the beginning of the project, the three Barind districts were marginally surplus food producers, however, with the introduction of DTWs, their surplus over the project period increased substantially. Income level increased because of increasing agricultural production, increased demand for labor and increased wage rates.

Besides implementing a comprehensive package of agricultural development activities/ interventions, BIADP also introduced various associated programs like afforestation, re-excavation of ponds, construction of cross-dams, installation and electrification of DTWs etc. All these components played a positive role in improving the livelihood of the people with positive and highly satisfactory economic returns. The total cost recovery of the project was worked out to be Tk. 1,067 million of which the recovery from the beneficiaries of irrigation interventions was Tk. 1,013 million (Table 3). The financial and economic annual total incremental benefits of the project for the year 1999-2000 were estimated at Tk. 2,917 million and Tk. 2,603 million, respectively. All this indicates that the investment of the project has been economically and socially profitable that has had direct impact on poverty alleviation.

Table 3. Statement of cost recovery and financial sustainability of BIADP in million Taka (BMDA, 2000)

Year	Total cost	No. of DTWs in operation	Cost of irrigation components	O and M cost of irrigation	O and M cost of others	Total cost recovery	Irrigation cost recovery
1986-90	965	529	667	106	22	104	80
1990-91	712	871	712	-	-	-	-
1991-92	170	2,193	162	31	1	22	22
1992-93	441	3,173	415	49	2	53	49
1993-94	641	3,650	547	45	5	66	61
1994-95	881	5,066	802	70	3	139	135
1995-96	720	5,516	655	44	3	151	146
1996-97	633	5,611	607	34	1	130	128
1997-98	397	6,044	353	54	6	130	126
1998-99	294	6,247	247	81	12	174	170
1999-00	111	6,185	97	45	6	99	96
Total	5,967		5,264	558	62	1,067	1,013

Present value of 1 million Taka = 16,000 USD (Approx.).

Benefit-Cost Analysis of Various Pump Technologies to Groundwater Irrigation

Detailed cost analysis made by the NWMP on tube well technologies operating in the agricultural sector shows that energy cost is about 70-80 percent and capital costs is only 22-26 percent of total annual cost for STWs. In Bangladesh, diesel (fuel) is taxed while electricity is subsidised. The operating costs of FMTWs are similar to that of STWs but can draw water from greater depths. The present trend in using STW is good enough as it meets the present need. It is envisaged that groundwater abstraction can be kept profitable with FMTW even with the receding water table if supplies of electricity are made available at affordable prices in the future. Supply of energy in terms of electricity and diesel fuel plays an important role in the steady expansion of irrigated agriculture.

To grow more food grains in dry *Rabi*-season under minor irrigation different types of irrigation technologies are used in Bangladesh. An NWMP study (Hossain et al., 2002) reveals that LLPs are the cheapest form of minor irrigation, with their generally low pumping lifts and technical simplicity (Table 4). Total annual costs of LLP diesel pumping are only Tk. 0.30/m^3 and Tk. 0.23m^3 at financial and economic prices, or Tk. 3300/ha and Tk. 2500/ha,respectively. STWs are the next cheapest mode. Typical diesel-powered STW operating under static water level of 5 m from the ground surface has average costs of Tk. 0.69/m^3 and Tk. 0.53/m^3 at financial and economic prices, or Tk. 7600/ha and Tk. 5800/ha, respectively. This is more than double the LLP costs. Tube well pumping costs increase rapidly as groundwater levels decline. For an average 7 m depth, diesel-powered STWs set into a pit of 2 m (DSSTWs) costs about Tk. 0.90/m^3 and Tk. 0.69/m^3, or Tk. 9900/ha and Tk. 7600/ha,respectively at financial and economic prices. However electricity-powered STWs with a lift of 7m costs around Tk. 0.40/m^3. FMTWs also suffer from high capital costs relative to the suction mode pumps. Although the annual financial cost of an electric FMTW (Tk. 0.87/m^3) is lower than a diesel DSSTW (Tk. 0.90/m^3), the capital investment is much higher. DTW irrigation has

Table 4. Annual minor irrigation costs (1998-99)

Technology	LLP	STW	STW	DSSTW	VDSSTW	VDSSTW	FMTW	DTW
Static water level (m)	4m	4m	5m	7m	9m	11m(1)	13m	13m
Average command area (Base Case) (ha)								
Diesel pumping	8	3.2	3.2	3.2	3.2	3.2	-	16
Electric pumping	16	4.4	4.4	4.4	4.4	4.4	4.6	22
Total annual costs with “average” pumpage								
Diesel: Financial	26,366	19,918	24,314	31,807	36,005	40,468	-	176,928
Diesel: Economic	20,207	15,307	18,635	24,385	27,903	31,341	-	134,554
Electric: Financial	21,322	13,597	15,332	19,340	24,477	28,024	41,027	149,230
Electric: Economic	22,879	13,449	15,480	19,726	25,025	29,152	39,891	139,176
Annual costs per ha with “average” pumpage								
Diesel: Financial	3,296	6,224	7,598	9,940	11,252	12,646	-	11,058
Diesel: Economic	2,526	4,783	5,824	7,620	8,720	9,794	-	8,410
Electric: Financial	1,333	3,090	3,485	4,395	5,563	6,369	8,919	6,783
Electric: Economic	1,430	3,057	3,518	4,483	5,687	6,625	8,672	6,326
Annual cost per m^3 water with “average” pumpage								
Diesel: Financial	0.30	0.57	0.69	0.90	1.02	1.15	-	1.01
Diesel: Economic	0.23	0.43	0.53	0.69	0.79	0.89	-	0.76
Electric: Financial	0.12	0.28	0.32	0.40	0.51	0.58	0.81	0.62
Electric: Economic	0.13	0.28	0.32	0.41	0.52	0.60	0.79	0.58

Source: NWMPP Note: (1) Use of VDSSTWs to pump from this depth is not common at present.

the highest capital costs of the four basic models. Electric DTWs are cheaper than diesel DTWs. Cost of electric DTWs is more then three times that of a diesel DSSTW.

Benefit-cost ratio determined from the NMWP study is shown in Table 5. The study shows that irrigation by LLP and STW, the most widespread forms of minor irrigation, are highly profitable in both financial and economic terms. For the two widely applicable models, LLPs, and STWs with an average static water level of 5m, both with diesel pump sets; the estimated average financial returns after deducting the full cost of irrigation are about Tk. 11,600/ha and Tk. 7300/ha, respectively. The benefit-cost ratios are 4.5:1 and 2.0:1. Even a DSSTW with a static water table of 7m yields a financial profit of Tk. 5000/ha and a benefit-cost ratio of 1.5:1.

Table 5. Benefit-cost ratios from minor irrigation (Hossain et al., 2002)

Irrigation technology	LLP	STW	STW	DSSTW	VDSSTW	VDSSTW	FMTW	DTW
Static water level (m)	4m	4m	5m	7m	9m	11m	13m	13m
Average command area (Base Case) ha								
Diesel Pumping	8	3.2	3.2	3.2	3.2	3.2	-	16
Electric Pumping	16	4.4	4.4	4.4	4.4	4.4	4.6	22
Annual irrigation benefits per ha (based on boro cropping) (Tk)								
Financial	14,900							
Economic	14,000							
Benefit-cost ratios at 12%								
Diesel: Financial	4.52 : 1	2.39 : 1	1.96 : 1	1.50 : 1	1.32 : 1	1.18 : 1	-	1.35 : 1
Diesel: Economic	5.54 : 1	2.93 : 1	2.40 : 1	1.84 : 1	1.61 : 1	1.43 : 1	-	1.66 : 1
Electric: Financial	11.18 : 1	4.82 : 1	4.28 : 1	3.39 : 1	2.68 : 1	2.34 : 1	1.67 : 1	2.20 : 1
Electric: Economic	9.79 : 1	4.58 : 1	3.98 : 1	3.12 : 1	2.46 : 1	2.11 : 1	1.61 : 1	2.21 : 1

Source: NWMPP estimates.

So, better operation and maintenance of DTWs, improving the management efficiency, increasing electrification of DTW, sinking new DTWs in the potential areas may increase crop production that can play important role in poverty alleviation.

Major Problems in Groundwater Development

The water resources of Bangladesh are facing different problems including quality hazards in many areas where the exposure to pollution from agriculture, urban areas and industrial sites as well as arsenic contamination in shallower groundwater aquifers makes the water unfit for human consumption and in some cases even for irrigation purposes. It has been estimated that the population of 61 districts has been suffering from arsenic contamination (DPHE, 2001).

To protect the population from water-borne diseases, primarily from the consumption of polluted and dirty surface water, effort has been made throughout the country during the past two decades to replace drinking water supplies from surface water with groundwater and millions of shallow tube wells (<100m deep) have been installed in the shallower part of the unconfined/leaky aquifers. Since the early 1990's, after the discovery of arsenic contamination in shallow groundwater, deeper tube wells have been installed (100- 250m depth) in an attempt to find safe groundwater for drinking water supplies. Most of these tube wells have little or no arsenic, but the wells often contain high concentrations of iron and high salinity. Below this level good quality groundwater can be found if confining clay bed separates the upper aquifer from deeper aquifer like many areas of lower delta (Figure 7).

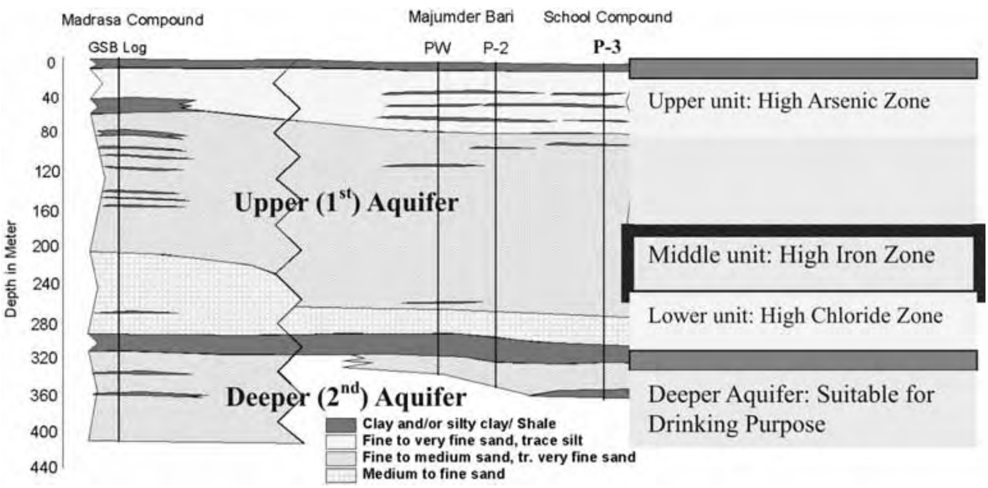

Figure 7. Generalized distribution of water quality hazard in lower deltaic plain aquifer, Sreerampur, Chandpur (BWDB, 2004)

Impact of Irrigation Pumping on Groundwater Drawdown

In rural areas, lowering of the groundwater table due to groundwater abstraction disturb seasonally shallow hand tube wells used for drinking water supply. Besides, the cost of irrigation pumping increases with the lowering of the water table. The over-withdrawal of groundwater for agriculture mainly causes drawdown in the dry season. However, the groundwater table regains its static water level in most of the country with sufficient recharge of rainwater (Figure 8-A).

In the highly populated urban areas, most noticeable in Dhaka city, recharge to the aquifers is much less than abstraction of groundwater. The lowering trend of groundwater level during the last 32 years is 20 to 30m with an average decline of more than 1.0 m/year. Continuous decline in water level with little or even no fluctuation has been observed (Figure 8-B). This lowering of the water level leads to increased pumping cost, abandonment of wells, and land subsidence.

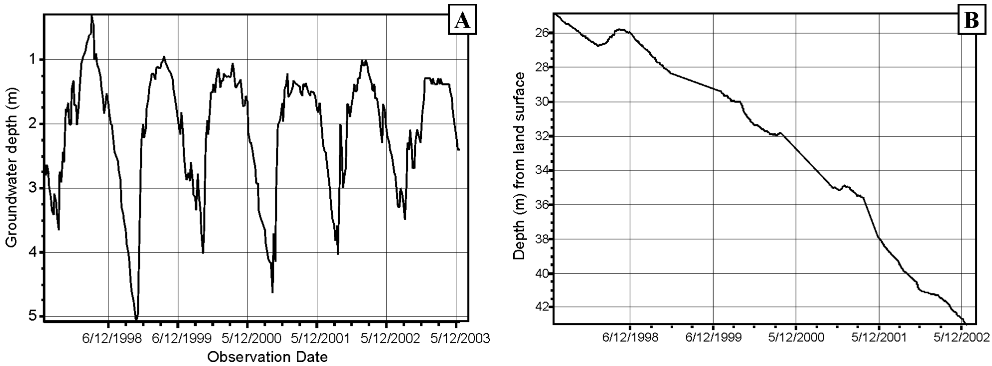

Figure 8. Groundwater table hydrograph from ground surface; A. Kachua, Chandpur; B. Banani, Dhaka City (BWDB, 2004)

Groundwater Pollution from Cities and Industries

Industrial activities are responsible for increased heavy metal levels in soils and sediments in many areas of the country. Sediment contamination by heavy metals is an important issue of increasing environmental concern. Increased unplanned urbanization and industrialization have already affected the environmental components; air, soil, sediment and water of the Dhaka city area. The tannery effluents discharged directly to the nature create environmental problems. Presence of higher accumulation of Cr, Al and Fe in topsoils (down to investigated 6m) with significant amount of Mn, Zn, Ni and Cu were observed (Figure 9), which has already influenced the quality of shallow groundwater.

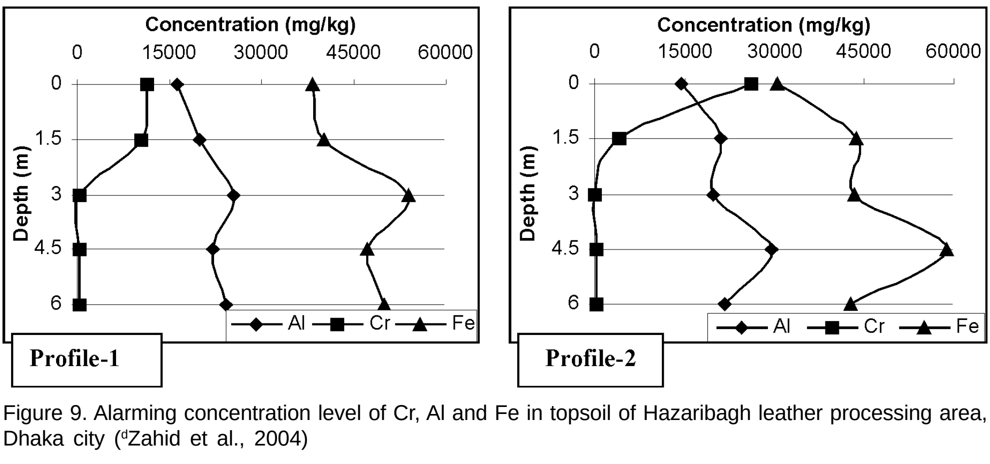

Figure 9. Alarming concentration level of Cr, Al and Fe in topsoil of Hazaribagh leather processing area, Dhaka city ([d]Zahid et al., 2004)

Groundwater Degradation from Agricultural Activities

Bangladesh has a very high population and aims for self-sufficiency in agricultural production. As a result, intensive farming with increased use of fertilizers and pesticides took place. Chemical fertilizers containing nitrogen, phosphorous and potassium are potential contamination sources. There is inadequate knowledge of the extent of this contamination and the impact on the groundwater resource. However, low levels of organochlorine pesticides (Heptachlor and DDT) have been detected at some locations. Higher ammonium and nitrate levels have also been found in shallow aquifers (Hossain, 1997).

Arsenic Contamination

In recent years, the presence of arsenic in shallow groundwater has disrupted the whole scenario of its use and since the last decade arsenic contamination in groundwater is considered an emergency health concern. It has been reported that out of 64 districts 61 are affected (GWTF, 2002). About 25 to 30 million or 25 to 30 percent rural population are at risk from arsenic contamination. In 1995, the presence of arsenic was confirmed in number of shallow and deep wells in different parts of the country. In 1996, Ground Water Hydrology Division of BWDB detected arsenic contamination in the western border belt of the country. Subsequently, patients have been identified as suffering from different types of arsenicosis and millions of tube wells contain arsenic in high levels of concentration. The arsenic-affected patients show arsenic skin lesions such as melanosis, leucomelanosis, keratosis, hyperkeratosis, dorsum, non-peting oedema, gangrene and skin cancer (Dhar et al., 1997).

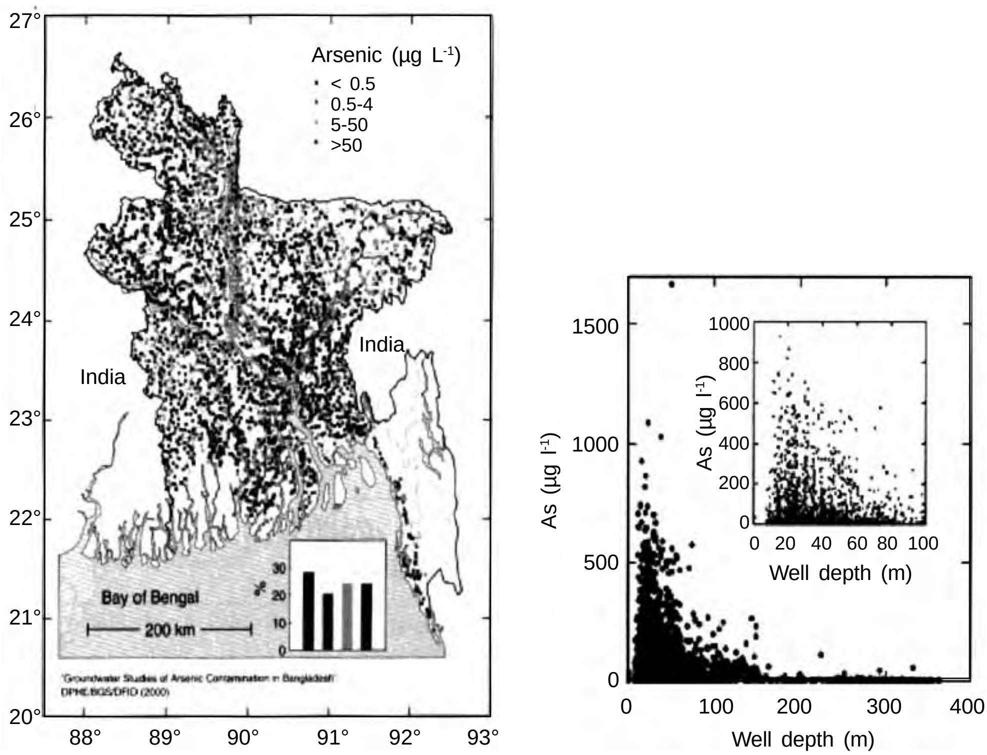

Figure 10. (A) Arsenic concentrations in shallow wells; (B) Distribution of arsenic with depth (DPHE-BGS, 2001)

The DPHE study project initially covered 252 upazilas (sub-districts) in the country. During phase-I, the rapid investigation phase, 2023 samples from 41 districts were collected and analyzed and 51 percent of total samples exceeded the WHO guideline (10 μg/l) and 35 percent of total samples exceeded Bangladesh standard (50 μg/l) for arsenic concentration (DPHE-BGS-MML, 1999). The older aquifers beneath the Barind and Madhupur Tracts are free of arsenic but the adjacent floodplains may be badly affected.

Salinity Intrusion

The most characteristic type of water quality degradation occurring in the coastal plain aquifer of Bangladesh is seawater intrusion. Fresh groundwater generally occurs in deep aquifer layers, below a sequence of other aquifer layers containing saline or brackish groundwater (DPHE-DANIDA, 2001). In the southern regions of Bangladesh groundwater abstraction often takes place from the upper aquifer. In this area, intrusion of saline water into the pumping well is often a problem due to heavy pumping. High rates of pumping for irrigation and other uses from the shallow unconfined aquifers in coastal areas may result in widespread saltwater intrusion, downward leakage of arsenic concentrations and the general degradation of water resources. Khulna city aquifers are reported to have marine influence due to increased anthropogenic pressure. Saline waters have already intruded major groundwater sources of Khulna city, and the fresh groundwater resources are becoming limited. The saline water also infiltrates to the groundwater from the surface water component as the rivers in the dry season carries saline water in the region (Datta and Biswas, 2004). The hydro-chemical and hydrogeological understanding of the salinity intrusion to the groundwater is limited and comprehensive studies are needed.

Conclusion and Recommendations

Groundwater is one of the most valuable natural resources and plays a vital role in the development process of the country. Its sustainable development and proper management can be achieved with a clear understanding of the groundwater system, its geology, hydrogeology, the subsurface flow and the response of the system considering seasonal, tidal and pumping stresses. As such, investigation of the aquifer systems, understanding of formation behavior, regular monitoring of groundwater storage and quality are important for the development and integrated management of water resource.

Management

Matching long-term withdrawals of groundwater to recharge is the principal objective of sustainable groundwater resource planning. Maintaining the water balance of withdrawals and recharge is vital for managing human impact on water and ecological resources. Management of groundwater resources, projecting the future development possibilities and socio-economic as well as environment impact assessment, can be achieved covering following aspects;

- Because of increasing demand of water and to reduce dependency on limited fresh groundwater resources, utilization of available surface water and conjunctive use should be stressed as per NWPo and other guidelines of the government. This will minimize the seasonal fluctuation rate of water table and lessen stress on groundwater resource
- Excessive withdrawal of groundwater for irrigation, industrial and domestic use needs to be controlled. Groundwater resources that can safely be abstracted from both upper and deeper aquifers need to be assessed properly
- Regional modeling of the groundwater systems has to be developed for effective water resource management to plan agricultural, rural and urban water supplies and to forecast the groundwater situation in advance for dry seasons
- Assessment of maximum or most valuable utilization of groundwater resources by developing priorities for long-term use considering widespread droughts, shifting populations and agricultural expansion to minimize the increasing stress on groundwater supply in an area. Assess groundwater pollution and alternative measures of protecting the resource in the future and safeguarding the public health
- Better operation and maintenance of tube wells, operating the installed and installable DTWs under an appropriate system acceptable to farmers, improving the management efficiency, crop diversification, increase in electrification of DTW, sinking new DTWs in the potential areas may increase crop production.

Investigations

In present scenario, besides proper investigation of shallow aquifer formations, exploration on the deeper formation of aquifer systems (250-400 m deep)- probable potential safe source of drinking water in many areas, is very important. But its development needs detailed studies to avoid saltwater intrusion and other possible water quality and quantity degradation. As such, following studies might be emphasized:

- Investigations on aquifer system and understanding of aquifer behavior; identification of the subsurface lithologic units, lateral and vertical extent of the aquifers, delineate fresh and saline groundwater interface in the coastal areas and characterization of the properties of aquifer sediments.
- Assessment of groundwater resources; determination of the performance characteristics of wells and the hydraulic parameters of the aquifers; the impact on withdrawal; the chemical characteristics and potability of the aquifers and identification of arsenic, iron and chloride distribution patterns in the aquifers.
- Investigation of the recharge mechanism of water in the deeper confined aquifers; evaluation of the impact of hydrogeologic heterogeneity and temporal variability in the flow system on the practical use of the aquifer for water supply.
- The intensive farming takes place with increased use of fertilizers and pesticides. The consequences of such intensive farming practice need to be analyzed by assessing pollution of groundwater from fertilizers and pesticide in upper

aquifers, vertical and horizontal extent of pollution migration, leaching mechanism, time of migration and remedial measures etc.

Monitoring

- Extend existing network of groundwater monitoring wells spatially and vertically in different aquifers for calculating recharge, monitoring fluctuation of water table and movement of groundwater.
- Increase the numbers of groundwater sampling stations and water quality laboratories for monitoring water quality and any possibility of saline water encroachment or quality hazards.
- Prepare models to simulate the movement of groundwater flows and mass transport system in the region and finally an evaluation of hydrogeology of safe aquifer of the area.
- Zoning of groundwater aquifers, STW/DTW areas, saline encroachment areas, initiation and implementation of small-scale irrigation project, establishment of water resource information system, strengthen and upgrade the existing groundwater data centers.

Capacity Building

- To facilitate the actions for sustainable development and management of groundwater resources of Bangladesh, strengthening and capacity building of appropriate organizations is required.
- Creation or identification of an organization like 'Ground Water Board/ Agency/Commission' has been recommended by the Ground Water Task Force (GWTF), 2002 and other experts. As Bangladesh Water Development Board has the mandate of investigating and monitoring the status of groundwater all over the country and is working in this field since about 4 decades, field and laboratory facilities as well as appropriate man power of this organization should be strengthened for effective management plan of groundwater resources to agricultural, rural and urban water supplies.
- Formulation of 'Groundwater Act' or 'Groundwater Conservation Act' recommended by the GWTF and experts to control all sorts of activities need to be enacted soon to ensure sustainable long-term use of groundwater.

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Availability, Status of Development, and Constraints for Sustainable Exploitation of Groundwater in China

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Abstract

China is one of the 13 most water-deficient countries in the world and water shortage is limiting the development of its economy. The authors present an overview of the availability, status of development, and constraints for sustainable exploitation of groundwater in China. Groundwater is the most important or exclusive water source in arid or semi-arid regions of north and northwest China. Average groundwater recharge in China is estimated to be 883.6 billion m^3/yr, approximating 31 percent of the nation's total water resources. Estimated allowable yield of fresh groundwater resource is 352.8 billion m^3/yr, or 40 percent of total available amount. Groundwater pollution occurs in many areas of the country, and especially in urban areas. Main pollution sources are industrial and domestic pollution. Current groundwater use approximates 20 percent of total water use of China. Groundwater in the North China Plains (NCP) is over-exploited, being 52 percent of its total water supply for all purposes. Total annual groundwater abstraction in China increased from 57.2 billion m^3/yr in the 1970's to 111.5 billion m^3/yr in 1999. Groundwater in south China has great potential for development. To accommodate new water resource management concepts and challenges, China has promulgated many laws and rules in the 1980s and the 1990s and still drafts complementarities and modifies previous ones. The policy shifted several years ago; the primary emphasis from structural engineering interventions to water supply and control problems, and to recognition of the need for a more comprehensive and diffused notion of water as a resource to be developed and managed in response to changing market criteria. Sustainable use of groundwater requires comprehensive efforts from scientists, decision makers and all individual water users. The most important things are: to enhance public awareness and knowledge of groundwater; and to create work environments for better communication among water managers, planners, decision-makers, scientists, water users, etc. and reduce the gaps among different parties.

Introduction

China is a country with relatively limited and uneven distributed water resources, yet it has to meet the challenge of supplying usable water to its 1.3

billion citizens. China is the third-largest country in the world, with land ranging from plains to mountains having some of the highest peaks in the world. Mountainous regions comprise 33 percent of the country, plateaus 26 percent, basins 18.8 percent, plains 12 percent and hills 9.9 percent.

China has the third-largest river in the world, the Yangtze River, stretching over 6,300 km. Other major rivers include the Yellow River (stretching 5,464 km), the second largest in China, and the Huai River, which is one of the most polluted. Aside from natural waters, China possesses the longest man-made river in the world, the Grand Canal in the eastern coastal area, reaching 1,801 km in length, from Hangzhou in the south, via Nanjing, Shandong, Tianjin to Beijing in the north (See Fig 1 for detail).

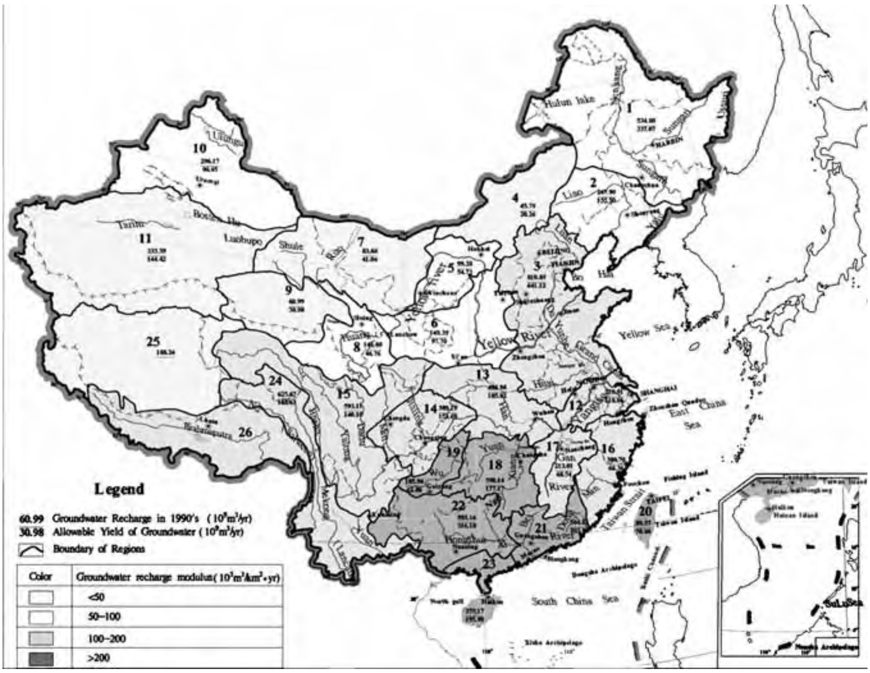

Figure 1. Distribution of groundwater resources in China

1.Hei-Song catchments; 2.Liao river catchments; 3.Huang-huai-hai region; 4.North Inner Mongolia plateau; 5.Ordos plateau and Yinchuan plain; 6.Loess plateau; 7.Hexi Corridor; 8.Upper reaches of Yellow River; 9.Saidam basin; 10.Dzungaria basin; 11.Tarim basin; 12.Lower reaches of Yangtze; 13.Middle reaches of Yangtze; 14.Sichuan basin; 15.Jinsha river catchments; 16.Min-zhe hilly land areas; 17.Boyanghu water systems; 18.Dongting water systems; 19.Wujiang catchments; 20.Taiwan; 21.Pearl river and Hanjiang; 22.Xijiang; 23.Lei-qiong areas; 24.Salween, Lancang catchments; 25.North Tibet plateau; 26.Brahmaputra

China is the most populous country in the world, and it is listed as one of the 13 most water-deficient countries in the world, having more than half of its cities suffering from a water deficit. The average total amount of water resources in China is 2812 billion m^3/yr (Chen, 1998), but the per capita water resource is only about 2200 m^3, which is only 31 percent of the world average. Table 1 shows the distribution of water resources in China. Water shortage and increasing levels of pollution are limiting development of the local economy, especially in agriculture and industry in many regions. Agricultural, industrial and urban entities all vie for limited precious water resources.

Influenced by monsoon climate, the distribution of water resources in China is extremely uneven in time and space. There is abundant water in the south but little land that can be used for agriculture due to the mountainous regions, while less water but more land is available in the north. Dryland makes up the majority of China's farmland (about 70 percent) and is affected greatly by water shortage, in the sense of unpredictable and unreliable rainfall. Most dryland is located in the north of China with arid or semi-arid conditions, of very low precipitation and a very high evaporation rate. Since agriculture is dependent upon water, the lack thereof can lead to poverty. Discrepancy between water availability and demand is becoming more and more serious, especially in the North and Northwest. The fundamental problem is that demand increases with increasing population, standard of living, urbanization and industrialization.

Table 1. Water resources in China in 2002[(1)]

Catchments/Regions	Rainfall (10^9 m^3)	Surface water (10^9 m^3)	Ground water (10^9 m^3)	Water deducted[(2)] (10^9 m^3)	Total water resources (10^9 m^3)	Per capita water res. (m^3)
Song-liao river	570.986	107.603	57.642	29.695	137.298	1157
Hai-river Basin	127.381	6.408	14.609	9.491	15.899	121
Huai-river Basin	237.591	44.536	34.366	25.647	70.183	343
Yellow River	322.487	35.766	33.401	11.574	47.340	428
Yangtze River Basin	2102.393	1078.831	270.493	10.248	1089.079	2521
Pearl River	987.692	522.721	124.435	2.392	525.113	3328
Southeastern	387.188	230.062	62.873	1.274	231.436	3233
Southwestern	888.702	563.983	172.506	0.068	564.051	26844
Inland Basins	636.609	134.419	99.393	11.312	145.731	5263
Total	6261.029	2724.329	869.718	101.701	2826.130	2200

Note: (1) Data from the annual report of 2002 by the Ministry of Water Resources PR China. Water resources in Taiwan, Hong Kong and Macao are not included in the table. (2) The water deducted is the water volume that has to be subtracted from the sum of surface and groundwater due to the interrelation between surface water and groundwater.

Total water use in China has increased in the past 5 decades (Table 2). It has been about 550 billion m^3 in recent years, being 5 times more than that in 1949 (103 billion m^3). Yet, the percentage of water use in agriculture has decreased from 97 percent in 1949 to 68 percent in 2002, which is because domestic and industrial use has substantially increased.

Availability of Groundwater Resources in China

Regional Hydrogeology of China

Groundwater resources comprise an important part of water sources in China. Especially in semi-arid and arid regions of north and northwest China, groundwater is the most important or exclusive water source.

Table 2. Total annual water use in China (10^9 m^3)

Year	Total water use	Industry	Agriculture	Domestic
1949	103.1	2.4 (2.33%)	100.1 (97.09%)	0.6 (0.58%)
1957	204.8	9.6 (4.69%)	193.8 (94.63%)	1.4 (0.68%)
1965	274.4	18.1 (6.60%)	254.5 (92.75%)	1.8 (0.66%)
1979	476.7	52.3 (10.97%)	419.5 (88.00%)	4.9 (1.03%)
1980	440.3	41.8 (9.5%)	370.7 (84.2%)	27.4 (6.3%)
1997	556.6	112.1 (20.1%)	391.7 (70.4%)	52.5 (9.4%)
1999	559.1	115.9 (20.7%)	386.9 (69.2%)	56.3 (10.1%)
2000	549.8	113.9 (20.7%)	378.4 (68.8%)	57.5 (10.5%)
2002	549.7	114.3 (20.8%)	373.8 (68.0%)	61.6 (11.2%)

Note: Data from annual reports by the Ministry of Water Resources and Liu and Chen (2001).

Physiographic and hydrogeological conditions of China vary greatly in different regions. From the 1950s, regional hydrogeological mapping, primarily on the scale of 1:200,000, has been carried out under the Ministry of Geology. Regional surveying has covered most areas of the territory.

Based on regional hydrogeological mapping, China is characterized by a great complexity of its regional hydrogeological conditions and may be divided into the following six main hydrogeological regions (Fig 2, Chen and Cai, 2000):

- The Songliao Plain and Huang-Huai-Hai Plain, with enormously thick unconsolidated sediments forming multiple aquifers recharged principally by vertical infiltration of rainfall.
- Inner Mongolian Plateau and Loess Plateau, an intermediate zone between the semi-humid zone in the east and the dry desert zone in the west.
- The Western Inland Basins, consisting mainly of the Hexi Corridor, Dzungaria Basin, Tarim Basin and Saidam Basin, typical arid desert land, usually with plenty of groundwater in broad piedmont plains.
- The Southeast and Central-south Hilly Land, characterized by different kind of rocks widely exposed, fissure water dominates in this area.
- The Southwest Karst Hilly Land, characterized by wide distribution of carbonate rocks, where karst water and subterranean drainage are well developed.
- The Tibet Plateau, with an average elevation of around 4000m. The aquifers are mainly of the permafrost or glacial genetic type and groundwater is entirely under the control of vertical zoning.

According to medium of aquifers, groundwater in China can mainly be classified as pore water, karst water and fissure water. Pore water is most prevalent and used most intensively. Karst water takes second place and fissure water last.

Available Groundwater Resources and the Distribution

Based on regional groundwater investigations and observation data mainly in the 1990s, it is estimated that total groundwater recharge (renewable fresh groundwater resources) in China amounts to 883.6 x 10^9 m^3/yr, approximating 31 percent of total water resources. Allowable yield of fresh groundwater resource is 352.8 x 10^9 m^3/yr, or 40 percent of total available amount (Ministry of Land and Resources, 2003). Allowable yield of brackish water (1-3 g/L in TDS) is 13 x 10^9 m^3/yr.

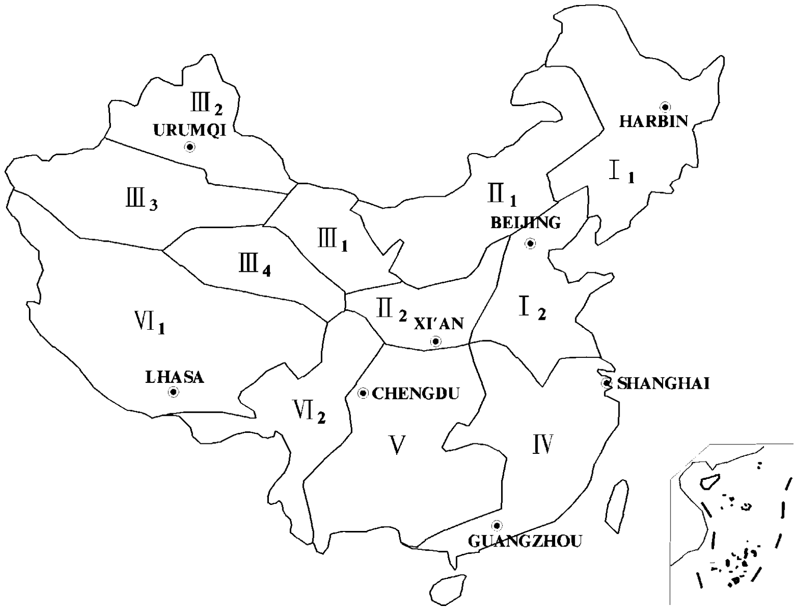

Figure 2. Hydrogeological regions in China (Insert: South China Sea)(Chen and Cai, 2000)
I_1. The Songliao Plain; I_2. Huang-Huai-Hai Plain; II_1. Inner Mongolian Plateau; II_2 Loess Plateau; III. The Western Inland basins; IV. The Southeast and Central-south Hilly Land; V. The Southwest Karst Hilly Land; VI. The Tibet Plateau

In the Standard for Hydrogeological Investigation of Water Supply (GAQSIQ and MOC, 2001), the allowable yield of groundwater resources is defined as: the water amount that can be sustainably abstracted from a groundwater system or a hydrogeological region by a certain rational pumping technique and scheme, resulting in a drawdown and variation of water quality that are within allowable ranges without any permanent damage to the geo-environments.

Distribution of regional groundwater in China has been estimated in 26 regions based on hydrogeological conditions (see Figure 1 and Table 3). Recharge modules for Pearl River Catchments is 322.4 x 10^3 $m^3/km^2{\cdot}yr$; Yangtze River Catchments 148.2 x 10^3 $m^3/km^2{\cdot}yr$; Yellow River Catchments is 61.1 x 10^3 $m^3/km^2{\cdot}yr$; and Northwest area is less than 50 x 10^3 $m^3/km^2{\cdot}yr$.

Groundwater in southern China is abundant, accounting for 71 percent of total national groundwater resources, while groundwater in northern China covering 60 percent of the land accounts for 29 percent only, and northwest regions covering one third of the land accounts for only 13 percent.

Besides, affected by population, farmland, and economy development, there exists great differences in groundwater availability per person and per ha farmland throughout the country. Water availability per person and per ha farmland is the lowest in the North China (Hai-river, Huai-river and Yellow River Basin), and the highest in southwest regions (Table 1). Groundwater per person in southeast and south-central regions is higher than north and northeast region of China. Groundwater per person in southwest is two times higher than the average of the country (Chen and Ma, 2002).

Table 3. Available groundwater resources in China(1)

Regions(2)		Average groundwater recharge in the 1990s		Allowable yield of groundwater	
		(10^9 m^3/yr)	(10^3 m^3/$km^2 \cdot yr$)	(10^9 m^3/yr)	(10^3 m^3/$km^2 \cdot yr$)
Yellow River Catchments	1. Hei-Song catchments	52.051	58.6	32.834	36.6
	2. Liao river catchments	24.647	86.3	15.474	109.1
	3. Huang-huai-hai region	63.533	114.6	51.210	101.8
	12. Lower reaches of Yellow River(3)	4.045	162.2	4.053	162.1
	6. Loess plateau	13.054	54.2	9.375	64.0
	5. Ordos plateau and Yinchuan plain	7.285	56.1	3.958	31.4
	8. Upper reaches of Yellow River	14.144	62.5	4.378	20.9
	Sum	38.528	61.1	21.764	43.0
Inland basins	4. North Inner Mongolia plateau	4.008	16.4	1.721	16.7
	7. Hexi Corridor	6.323	20.4	3.206	11.7
	9. Saidam basin	6.099	29.6	3.098	17.1
	10. Dzungaria basin	29.617	72.4	9.045	48.7
	11. Tarim basin	33.339	31.7	14.442	30.2
	25. North Tibet plateau	10.520	27.0	-	-
	Sum	89.906	34.5	31.512	25.8
Yangtze river catchments	12. Lower reaches of Yangtze	18.082	163.1	9.814	88.6
	13. Middle reaches of Yangtze	49.486	173.1	18.582	67.8
	14. Sichuan basin	38.919	196.4	15.369	77.6
	15. Jinsha river catchments	59.244	86.1	14.210	30.1
	17. Boyanghu water systems	21.300	133.8	6.854	44.1
	18. Dongting water systems	59.014	231.2	17.717	69.4
	19. Wujiang catchments	18.596	209.6	6.286	70.8
	Sum	264.641	148.2	88.832	57.2
Pearl river catchments	21. Pearl river and Hanjiang	56.181	382.0	20.086	222.8
	22. Xijiang	98.516	296.0	31.618	101.1
	25. Sum	154.697	322.4	51.704	128.3
	16. Min-zhe hilly land areas	38.578	189.7	6.797	57.2
	20. Taiwan	9.056	251.6	5.686	157.9
	23. Lei-qiong areas	37.233	415.3	19.406	216.5
	24. Nujiang(Salween), Lancang catchments	62.122	152.8	15.865	44.1
	26. Brahmaputra (Yaluzangbu)	52.701	136.7	15.747	40.8
	National total	883.648	106.1	352.778	57.0

Note:: (1) Data from Ministry of Land and Resources, China, 2003; (2) Location see Fig. 1.; (3)The number of Huang-Huai-Hai region includes 4.045 billion m^3/yr of the lower reaches of Yellow River.

Status of Groundwater Development in China

General Status

Groundwater abstractions in China in the past three decades are shown in Table 4. From the table we can see that total annual groundwater abstraction increased from 57.2 billion m^3/yr in the 1970s to 111.6 billion m^3/yr in 1999.

Current groundwater abstraction accounts for 20 percent of total water use in China.

The area with the highest intensity of groundwater exploitation is north China plains (NCP) where groundwater plays a very important role to water supply and approximately provides 52 percent of total water use. For urban ,domestic and industrial use, groundwater contributed 80~90 percent in 1999. For agricultural use, groundwater contributed approximately 38 percent on the average in the NCP. In Hebei province, groundwater occupies 75 percent of total water supply and beyond 50 percent in Shanxi and Henan province (MLD, 2003).

Influenced by the distribution of water resources and population and economic development and groundwater exploitation conditions, the imbalance of groundwater supply and demand is very serious in cities of north China. So far, there are almost 400 cities whose main water sources are groundwater. More than 300 cities suffer from water stress and scarcity, which are mainly located in the north China.

Furthermore, groundwater pollution in urban areas is rather serious. An uncompleted statistics showed that there are 136 large and medium cities where groundwater has been contaminated to varying degrees. Main pollution sources are industrial and domestic pollution. Groundwater has been polluted also in some agricultural regions, mainly near suburbs. There were over 1.33 M ha farmland irrigated with industrial wastewater in 2000, directly polluting groundwater there. Groundwater is polluted by pesticides and fertilizers in some areas (Chen and Cai, 2000). There are observation networks of groundwater throughout China; some wells are monitored thrice a year and some once a year.

Over-exploitation of Groundwater in Northern China

Groundwater in northern China (especially Hebei, Beijing and Tianjin provinces) has been intensively exploited. In most areas of northern China, especially large and medium sized cities, groundwater has been seriously overexploited (CIGEM, 2003).

For example, actual groundwater abstraction in Hebei province in 1999 was 14.946 billion m^3 (including 2.196 billion brackish groundwater of TDS 1-5g/L), but its recharge of fresh groundwater is estimated at 13.160 billion m^3 and the allowable yield of fresh groundwater is only 9.954 billion m^3/yr. This means that about 1.8 billion m^3 of fresh groundwater is overexploited every year. The overexploitation has resulted in serious environmental problems.

Because of the monsoon influence, the rainfall and runoff in the semi-arid Hebei are highly variable over the year, with, 60-70 percent of the annual precipitation (500-600mm) and runoff being concentrated between June and August. This water resource seasonality thus produces a spectrum of natural disasters such as spring droughts, autumn floods, soil salinization and alkalization, saline groundwater, which limit the expansion of agriculture in the area. In addition, with the development of agriculture since the 1980s, long-term groundwater over-extraction has led to a reduction in volume of fresh unconfined groundwater and continued lowering of groundwater levels for deep fresh confined water. This has resulted in serious environmental problems such as seawater intrusion, saline connate water invasion into fresh groundwater, land subsidence, etc. Consequently, the conflicts between socio-economic development and environmental protection become increasingly critical (Jin et al., 1999b).

Table 4. Groundwater abstractions in China in last three decades ($10^9 m^3$/yr.)

Provinces, autonomous regions or Municipalities	Mean annual abstraction in 1970s	Mean annual abstraction in 1980s	Mean annual abstraction in 1999	Change in abstraction 1980s-1970s	Change in abstraction 1999-1980s
Beijing	2.562	2.733	2.715	0.171	-0.018
Tianjin	0.714	0.809	0.633	0.095	-0.176
Hebei	11.403	13.900	14.946	2.497	1.046
Shanxi	2.628	3.030	4.199	0.402	1.169
Inner Mongolia	-	-	5.987	-	-
Liaoning	2.675	4.688	6.869	2.013	2.181
Jilin	0.935	1.300	2.992	0.365	1.692
Heilongjiang	2.809	5.821	6.500	3.012	0.679
Shanghai	0.078	0.112	0.104	0.034	-0.008
Jiangsu	0.195	0.655	1.834	0.460	1.179
Zhejiang	0.090	0.409	0.608	0.319	0.199
Anhui	0.920	1.071	1.848	0.151	0.777
Fujian	0.379	0.559	0.607	0.180	0.048
Jiangxi	0.524	0.828	1.251	0.304	0.423
Shandong	9.014	10.270	12.299	1.256	2.029
Henan	7.730	8.700	12.972	0.970	4.272
Hubei	0.051	0.923	1.397	0.872	0.474
Hunan	-	0.184	2.587	0.184	2.403
Guangdong	-	-	2.200	-	-
Guangxi	0.226	1.024	1.304	0.798	0.280
Hainan	0.290	-	0.492	-0.290	0.492
Chongqing	0.120	0.352	0.857	0.232	0.505
Sichuan	1.729	2.083	2.816	0.354	0.733
Guizhou	2.223	2.668	3.333	0.445	0.665
Yunnan	-	0.067	0.628	0.067	0.561
Tibet(Xizang)	-	-	0.166		-
Shaanxi	2.645	2.368	3.419	-0.277	1.051
Gansu	1.818	2.006	2.622	0.188	0.616
Qinghai	0.095	0.263	0.540	0.168	0.277
Ningxia	0.221	0.456	0.555	0.235	0.099
Xinjiang	1.500	3.750	5.135	2.250	1.385
Taiwan	3.631	3.801	7.139	0.170	3.338
National total	57.205	74.830	111.554	17.625	36.724

Note: data from the Ministry of Land and Water Resources, 2003.

Groundwater level depth for the deep freshwater in NCP was in the order of 20-100 m in 2001, but it was near surface, even artesian in the 1960s. Rates of groundwater level declines for the deep fresh aquifers in depression cones are 1-2 m/yr. Cangzhou, a coast city in eastern Hebei plain, is one of the cities with most serious water level decline of deep confined aquifers, 100 m decline since the 1960s. The water head declines have resulted in land subsidence, degradation of water quality, and harmful ions being released during consolidation of the aquitards, besides increased costs of pumping.

The water table depth of the shallow groundwater in 90 percent of the areas of NCP was larger than 2 m, 50 percent being larger than 10m in 2001. The lowering of water table has resulted in some disadvantages to ecology and environment, but one positive result is that soil salinization is decreasing in most areas of the plain.

In some areas or cities of China, although groundwater exploitation is smaller than allowable yield on the whole catchments, local overexploitation has happened because of over-concentrated exploitation with high intensity in certain areas (Wu et al., 2004). This also resulted in groundwater table decline, land subsidence and water quality degradation.

Great Potential of Groundwater Exploitation in Southern China

Since rainfall and surface water in southern China is relatively abundant, large and medium sized cities in southern China mostly utilize surface water as main sources for water supply. Currently, the contribution of groundwater to water supply in most areas of southern China is low, and groundwater development has great potential.

However, many areas in southern China have shifted to use good quality groundwater for water supply because surface water has been contaminated with the development of economy. The proportion of domestic water use from groundwater is increasing year by year, e.g., Guangzhou, Guangdong Province, and Fuzhou, Fujian province in southern China. Groundwater abstraction in Gaungzhou city accounts for 96 Mm^3 in 1997, of which 52 Mm^3 was for domestic use, 18 Mm^3 for industry and 26 Mm^3 for agriculture; its groundwater abstraction is planned to be 206 Mm^3 in 2005. Allowable yield of groundwater in Guangzhou is estimated at 403.85 Mm^3/yr (Wu et al., 2004).

Strategies for Sustainable Use of Groundwater

Problems and Constraints for Sustainable Exploitation of Groundwater

Main problems of unsustainable exploitation of groundwater in China are irrational abstraction or over-exploitation of groundwater in northern and northwest China and its associated problems and groundwater pollution in many areas. These certainly threaten sustainable development of the local economy. In addition, there are 41.08 M people (12.66 M in northwest) from 569 counties in West China being short of drinking water, usually areas associated with poverty (CIGEM, 2003).

Besides uneven distribution of water resources and the natural conditions of drought, the water shortage situation is aggravated by irrational development and utilization of groundwater, poor management of water resources and poor studies of groundwater (in some areas). While water shortage occurs widely, a large amount of water is wasted. While over-irrigation has resulted in soil salinization and water-logging in some areas, over-use of surface water and over-exploitation of groundwater has resulted in soil desertification and environmental deterioration in other areas of the same river basin. For example, in the Sangong river catchments, North of Xinjiang Autonomous Uygur Region (XAUR), Northwest China, groundwater has been intensively abstracted in the diluvium/alluvium fans, and then conducted to reservoirs in the alluvium plain for irrigation in the last three decades. Observations show that the water table is significantly declining in the alluvium fans, but rising in the alluvium plain from irrigation and the plain reservoirs. This water table rising has resulted in serious soil salinization in the arid area.

In the Hebei plain (main part of NCP) deep fresh water is extracted, whereas the shallow brackish groundwater is not used much. Management options for water problems in the plains include water demand management on the basis of water resource conditions, like: limiting water intensive industries, restricted pumping of deep fresh water; use of brackish water for irrigation; extension of water-saving irrigation; reuse of wastewater and so on (Zhang et al., 1994; Jin et al., 1999a). The use of shallow brackish water will make recharge of rainfall to shallow groundwater more effective (Jin et al., 1998; 1999a). Many field experiments and farmer practices in the past three decades have proved that brackish water with 2-5 mg/L in TDS can be used for irrigation and water-saving irrigation and brackish water use have great potential in NCP. Practices of water-saving irrigation in NCP have advanced somewhat, while irrigation quotas have been significantly reduced in the past decade. Water-saving irrigation and brackish water irrigation are the principal ways for sustainable use of groundwater in the plain. However, further extension of management practices to water-saving irrigation, brackish water irrigation, and restricting abstraction of deep fresh water is facing difficulty.

The reasons of irrational use of water or irrational abstraction of groundwater are mainly inadequate water management institutions and policies, including:

- Poor awareness and recognition of the public (especially private farmers in China) to water shortage and risk of irrational use of groundwater;
- Un-coordinated administration of a river basin;
- Multi-agency sharing of water resources management (leads to a situation where all agencies are partly responsible, but none is readily liable for the damage);
- Separation of water quantity management and pollution control;
- Low prices, even cost-free use of water for agriculture, leads to water wastage. Table 5 shows that the water price in NWC is in the order of 0.6 -7.5 cents per m^3 in 1998.

Table 5. Water price for agriculture use in North China in1998 (Yuan/m^3)

Provinces	Water price	Provinces	Water price
Beijing	0.020	Gansu	0.030
Hebei	0.075	Inner Mongolia	0.023
Shanxi	0.062	Ningxia	0.006
Tianjin	0.040	Qinghai	0.040
Heilongjiang	0.024	Shaanxi	0.039
Ji'ning	0.030	Xinjiang	0.018
Liaoning	0.030		

The above problems or constraints for sustainable exploitation of groundwater has received significant attention by scientists, economists and politicians in the past decade, but still remain unresolved.

Enacting Laws and Rules for Groundwater Management

To accommodate new water resource management concepts and challenges, China promulgated its first version of the Water Law in 1988 and a modified version of the Water Law in 2002. Related laws or rules include: Byelaw for Soil and Water Conservation (1982); Implementation Rules for License of Water Intake (1993); Law for Prevention and Cure of Water Pollution, promulgated in 1984 and modified in 1996; Implementation Rules to the Law for Prevention and Cure of Water Pollution, promulgated in 1989, modified in 2000; Administrative Rules to Water Resource Conservation for Construction Projects, promulgated in 2002; and so on.

According to these laws and rules, China's water program must serve as the regulatory framework for a system that rationalizes and substantiates water and the water infrastructure as public economic goods in the transition to a market economy, with a preeminent role for the Ministry of Water Resources (MWR) as the leading government body responsible for overall water planning, monitoring, research, and development. MWR also oversees national-level policymaking and inter-provincial policy coordination, and flood and drought protection and control. Ministry of Construction, Ministry of Land and Resources (MLR), Environmental Protection Agency (EPA) participates in planning, research, development and protection of water resources.

The policy shifted dramatically several years ago from primary emphasis on planned structural engineering interventions (*gongchengshuili in Chinese*) to address water supply and control problems, and to recognition of the need for a more comprehensive and diffuse notion of water as a resource (*ziyuanshuili in Chinese*) to be developed and managed in response to changing market criteria.

Specific laws and rules for groundwater development in major river basins are being drafted. This is very important to examine and approve permits to groundwater intake, especially in water scarce areas.

Implementation and enforcement of these laws and rules are still confronting difficulties. One of the reasons may be that the laws and rules are not adaptive enough to local situation and the market economy. The low water price maybe a reason resulting in water waste. However, to increase water price may bring more burden to poor farmers, which may cause conflict between farmers and water authorities. Obviously the capacity of water management is still not efficient and powerful enough.

Well Investigations and Evaluation of Groundwater Resources

China has done a lot of work on investigation and evaluation of groundwater and regional hydro-geological mapping, but the results in many cases are not presented in formats suitable enough for examining and approving permits to groundwater intake and practical schemes of groundwater exploitation. Schemes of groundwater development should be easily operational for policymakers at different levels and for individual water users.

Sustainable groundwater development and management is a complex task. As hydrologists or hydro-geologists or engineers of water resources, we should make our proposed schemes/planning of groundwater development user-friendly, easy to understand on the basis of well investigation and evaluations, and with consideration of user's demand. The proposed schemes should be optional for users or decision makers.

Future Directions

Achieving sustainable use of groundwater is a shared task or duty for scientists, decision makers and all individual water users. It is an issue of multiple disciplines, and needs efforts from all parties.

Scientific and Technical Aspects

Hydro-geologists and hydrologists have had compelling professional responsibilities for safe and reliable use of both surface and groundwater. These include the development of scientific principles and the application of these principles to satisfy the needs of society for sustained development.

Besides development of basic understanding and scientific principles of flow and transport of groundwater, further research needs to include:

- Development of more effective conceptual and numerical models for flow and transport in large heterogeneous media (especially in fractured and soluble rocks), including more refined transport models that couple flow and reactions.
- Better monitoring, investigation, evaluation of groundwater to establish user-friendly information systems at different levels for researchers, decision-makers and individual users.
- Better workable planning of groundwater development and utilizations, and user-friendly decision support systems for decision-makers. Based on sustainable use of water resources, this workable planning should be flexible to satisfy some biases of decision-makers and users and with enough consideration of all aspects related to water use, such as conjunctive use of surface and groundwater,

well locations, pumping rates and penetration depth to aquifers, regional and local economic development, environmental protection, etc.
- Better techniques, e.g. well-setup for both water pumping and injections in fine materials of aquifers with low flow rates, water-saving irrigation and drainage, harmful compounds clean up, etc.

Non-technical Aspects

According to our investigation, the main reason for irrational exploitation of groundwater is the gap among groundwater researchers, decision-makers and water users. Therefore we suggest:
- Strengthen public propaganda and education to enhance public awareness and knowledge of groundwater. Because of time constraints on planners, legislators and water managers, we can no longer assume that publication of articles in scientific journals, or even popular literature, will necessarily reach the appropriate decision-makers and stakeholders. Governmental institutions, universities, professional societies and other non-governmental organizations must devote efforts to develop programs to improve groundwater literacy of the public. It is particularly important for young children to become conscious of and sensitive to nature and the environment. These children are the future decision-makers. Such outreach will eventually demonstrate the desirability of funding for hydrogeology and related sciences (Back el al., 1997).
- Capacity building for sustainable water management, including adoption of laws and rules for groundwater management from national to river basin level, in order to force and guarantee that all planners, legislators, water managers and water users are serving to sustainable use of groundwater in their daily activities.
- Creating work environments for better communication and sharing data/ information among water managers, planners, decision-makers, scientists, water users and others to exchange ideas and knowledge for mending the gaps among different parties, including international exchange and cooperation.

Conclusions

- China is listed as one of the 13 most water-deficient countries in the world based on per capita water availability. The averaged total amount of water resources in China is 2826 billion m^3/yr, and the per capita water resource is about 2200 m^3, which is only 31 percent of the world average. The distribution of water resources in China is extremely uneven in time and space. In the South, there is abundant water but little land that can be used for agriculture while less water but more land are available in the north. Water shortage is limiting the development of China's economy.
- Groundwater is the most important or exclusive water source in arid or semi-arid regions of north and northwest China. Average groundwater recharge in China estimated to be 883.6 billion m^3/yr, approximating 31 percent of total water resources. Allowable yield of fresh groundwater resource is 352.8 billion m^3/yr.

Groundwater pollution occurs throughout China, being rather serious in urban areas. Main pollution sources are industrial and domestic pollution. Pesticides and fertilizers in some agricultural areas also pollute groundwater

- Total annual groundwater abstraction in China increased from 57.2 billion m^3/yr in the 1970s to 111.6 billion m^3/yr in 1999. Current groundwater consumption is approximating 20 percent of total water use of China. Groundwater in NCP accounts for 52 percent of total water use, where groundwater in Hebei province occupies 75 percent of total water supply and beyond 50 percent in Shanxi and Henan province.

  In most areas of northern China, especially cities, groundwater has been over-exploited, but groundwater in south China still has great potential for development.
- To accommodate new water resource management concepts and challenges, China has promulgated many laws and rules in the 1980s and the 1990s and still drafts complementarities and modifies previous ones.

  A dramatic policy shifted several years ago from primary emphasis on planned structural engineering interventions to address water supply and control problems and to recognize the need for a more comprehensive and diffuse notion of water as a resource to be developed and managed in response to changing market criteria.
- Achieving sustainable use of groundwater is a shared task or duty for scientists, decision makers and all individual water users. The most important things are to enhance public awareness and knowledge of groundwater and to create a work environment for better communication and sharing dada/ information among water managers, planners, decision-makers, scientists, water users and others to exchange ideas and knowledge and reduce the gaps between different parties, including international exchanges and cooperation.

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Status of Groundwater and Policy Issues for its Sustainable Development in India

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Abstract

There has been unprecedented groundwater development in India due to which the irrigation potential has increased manifold from 6.5 M ha to 45.7 M ha by the end of the VIII Plan. Out of an estimated maximum irrigation potential of 81.4 M ha in the minor irrigation sector, 64.0 M ha (79 percent) is estimated to be associated with groundwater.

The present paper deals with the groundwater resources availability in different parts of the country, bringing out areas, which are under stress, and also areas where groundwater development is at a relatively low level and further development of groundwater is possible. The contamination of groundwater due to geo-genic sources is also discussed in this paper with special emphasis on the arsenic and fluoride contamination, which has adversely affected a large population in the country.

Several issues need to be addressed for a proper approach to sustainable management of groundwater. The approach so far has been more towards the development of the resource rather than the management of it, which has resulted in haphazard development and over-development in some areas and contamination in other areas. The legal provision of groundwater rights to the landowner has lead to indiscriminate development of groundwater. Shortages of water in many areas and also the land ownership rights have lead to the development of water markets all over the country and especially in the water scarce areas. Sustainable groundwater management would require that groundwater is not considered in isolation but should also include artificial recharge and conservation, conjunctive use, land use planning as per the availability of water, and taking appropriate measures to avoid pollution. In the present scenario of scarcity of groundwater resources, the provision of free or subsidized power in the agriculture sector also needs to be given a fresh look.

Introduction

People around the world have used groundwater as a source of drinking water and even today more than half of the world's population depends on groundwater for survival. Groundwater has played a significant role in maintenance of India's economy, environment and standard of living. Besides being the primary source of water supply for domestic and many industrial uses, it is the single largest and most productive source of irrigation. Out of the ultimate irrigation potential of

81.4 M ha in India, in the minor irrigation sector, 64.0 M ha (79 percent) is from groundwater. It also provides water security during prolonged drought periods.

Groundwater Scenario in India

The total annual groundwater recharge in India is estimated at 432 billion cubic meters (BCM). After deducting the natural loss to the system, the net annual groundwater availability in the country is 361 BCM. The total annual groundwater draft is 150 BCM. In the states of Haryana, Punjab and Rajasthan, the stage of groundwater development is more than 85 percent and in Haryana and Punjab, heavy groundwater withdrawal have likewise resulted in high stage of groundwater development. In some parts of the country, such as the North Eastern States, groundwater development has not picked up yet. Presently, 673 assessment units of the country (see explanation in Table 1) are 'over-exploited' where the annual groundwater extraction exceeds the annual recharge. 425 assessment units are 'dark' or 'critical' where the groundwater development has reached to a high level, i.e. > 85 percent. Remaining 7091 blocks have been categorized as 'safe', having adequate groundwater resources for further development (Table 1).

Apart from the dynamic resource, a vast amount of in-storage resource (non-replenishable) is available at deeper levels. A first approximation indicates that the total in-storage groundwater reserve is around 10,812 BCM. In-storage groundwater reserves are particularly abundant in the alluvial deposits of Indo-Gangetic-Bramhaputra valley spreading in the northern and northeastern parts of the country.

The behavior and distribution of groundwater in the Indian sub-continent is not even. In fact it is complicated due to the occurrence of diversified geological formations and complex tectonic framework, climatic dissimilarities and various hydro-chemical conditions. The state wise availability of groundwater is summarized in Table 2.

Priority issues in the groundwater sector vary from place to place depending on the existing hydro-geological setup and the stress effect on it as a result of human interference. Groundwater is becoming an increasingly popular resource because of the relative ease and flexibility with which it can be tapped. Groundwater development has also occupied an important place in poverty alleviation policies because of its role in stabilizing the Indian agriculture and as means for drought management. During periods of droughts, additional dependence is laid on this resource since storage levels in surface water reservoirs dwindle and the impact of vagaries of weather on groundwater is not as pronounced and is delayed.

The average stage of groundwater development in the country, as estimated in 1991, was 32 percent. In March 2003, the average stage of development had reached approximately 42 percent. This is also evident from the growth of groundwater abstraction structures from the pre-VIII plan period till date. The number of groundwater abstraction structures (dug wells, shallow and deep tube wells) has increased from merely 4 million in 1951 to more than 17 million in 1997. With the growth of groundwater abstraction structures, there has been an increase in irrigation potential created from groundwater from 6.5 M ha to 45.7 M ha by the end of the VIII Plan. This rapid pace is likely to continue till the full irrigation potential estimated to be available from groundwater is created by approximately 2007.

Table 1. Groundwater development levels in India

	States	Number of assessment units	No. of assessment units			
			Over-exploited		Dark/Critical	
			No.	%	No.	%
1.	Andhra Pradesh	1157	118	10.20	79	6.83
2.	Arunachal Pradesh	59	0	0.00	0	0.00
3.	Assam	219	0	0.00	0	0.00
4.	Bihar	394	6	1.52	14	3.55
5.	Chhattisgarh	145	0	0.00	0	0.00
6.	Delhi	6	3	50.00	1	16.07
7.	Goa	12	0	0.00	0	0.00
8.	Gujarat	180	41	22.78	19	10.56
9.	Haryana	111	30	27.03	13	11.50
10.	Himachal Pradesh	69	0	0.00	0	0.00
11.	Jammu & Kashmir	69	0	0.00	0	0.00
12.	Jharkhand	193	0	0.00	0	0.00
13.	Karnataka	175	7	4.00	9	5.14
14.	Kerala	151	3	1.99	6	3.97
15.	Madhya Pradesh	312	2	0.64	1	0.34
16.	Maharashtra	2316	154	6.65	72	3.11
17.	Manipur	29	0	0.00	0	0.00
18.	Meghalaya	39	0	0.00	0	0.00
19.	Mizoram	12	0	0.00	0	0.00
20.	Nagaland	52	0	0.00	0	0.00
21.	Orissa	314	0	0.00	12	8.70
22.	Punjab	138	81	58.70	80	33.76
23.	Rajasthan	237	86	36.29	0	0.00
24.	Sikkim	4	0	0.00	37	9.61
25.	Tamil Nadu	385	138	35.84	0	0.00
26.	Tripura	38	0	0.00	20	2.44
27.	Uttar Pradesh & Uttaranchal	819	2	0.24	61	22.18
28.	West Bengal	275	0	0.00	61	22.18
	Total States	7910	671	8.48	424	5.36
	Union Territories	18	2	11.11	1	5.56
	Grand Total	7928	673	8.49	425	5.36

Notes: 1. Unit of Assessment : Andhra Pradesh –Basin, Maharashtra –Watershed(Command/Non-command wise); Gujarat,Karnataka -Taluka : Rest of the States – Blocks 2. Methodology for Estimation : Groundwater Estimation Committee(GEC) Guidelines '97 – Andhra Pradesh, Chhattisgarh, Jammu & Kashmir, Kerala, Maharashtra, Orissa, Rajasthan, Tamil Nadu, Uttar Pradesh, Andaman & Nicobar Island. GEC '84 – Rest of the states. 3. Criteria for Categorisation – Over-exploited – GEC '84 > 100%, GEC '97 >100%. Declining trend in both pre & post monsoon water level.Dark – GEC '84 > 85% & < = 100%, Critical-GEC '97 < 100%, Declining trend in both pre & post monsoon water level OR > 100%.

Table 2. State wise availability of groundwater resources

Sl. No.	State	Total replenishable groundwater resource BCM/Yr	Provision for domestic, industrial and other uses BCM/Yr	Available groundwater resources for irrigation BCM/Yr	Net draft BCM/Yr	Balance groundwater resources for future use BCM/Yr	Level of groundwater development (%)
1.	Andhra Pradesh	35.29	5.29	30.00	8.57	21.43	28.56
2.	Arunachal Pradesh	1.44	0.22	1.22	-	1.22	Neg
3.	Assam	24.72	3.71	21.01	1.84	19.17	8.75
4.	Bihar	26.99	4.05	22.94	10.63	12.31	46.33
5.	Chattisgarh	16.07	2.41	13.66	0.81	12.85	5.93
6.	Delhi	0.29	0.18	0.11	0.12	-	-
7.	Goa	0.22	0.03	0.19	0.02	0.17	8.30
8.	Gujarat	20.38	3.06	17.32	9.55	7.77	55.16
9.	Haryana	8.53	1.28	7.25	8.13	0.00	112.18
10.	Himachal Pradesh	0.37	0.07	0.29	0.03	0.26	10.72
11.	Jammu & Kashmir	4.43	0.66	3.76	0.03	3.73	0.81
12.	Jharkhand	6.53	0.98	5.55	1.84	3.71	33.13
13.	Karnataka	16.19	2.43	13.76	4.76	9.00	34.60
14.	Kerala	7.90	1.31	6.59	1.46	5.13	22.17
15.	Madhya Pradesh	34.82	5.22	29.60	8.02	21.58	27.09
16.	Maharashtra	37.87	12.40	25.47	9.44	16.04	37.04
17.	Manipur	3.15	0.47	2.68	Neg.	2.68	Neg.
18.	Meghalaya	0.54	0.08	0.46	0.02	0.44	3.97
19.	Mizoram*	1.40*	0.21*	1.19*	Neg.	1.19*	Neg.
20.	Nagaland	0.72	0.11	0.62	Neg.	0.62	Neg.
21.	Orissa	20.00	3.00	17.00	3.61	13.39	21.23
22.	Punjab	18.66	1.87	16.79	16.40	0.00	97.66
23.	Rajasthan	12.71	1.99	10.71	9.26	1.45	86.42
24.	Sikkim	0.07*	0.01*	0.06*	Neg.	0.06*	Neg.
25.	Tamil Nadu	26.39	3.96	22.43	14.45	7.98	64.43
26.	Tripura	0.66	0.10	0.56	0.19	0.38	33.43
27.	Uttar Pradesh	81.12	12.17	68.95	32.33	36.62	46.89
28.	Uttaranchal	2.70	0.41	2.29	0.82	1.47	35.78
29.	West Bengal	23.09	3.46	19.63	7.50	12.13	38.19
	Total States	433.00* (431.77)	71.14* (70.92)	361.98* (360.73)	149.82	212.78* (211.53)	41.53
	Total Union Territories	0.442* (0.116)	0.025* (0.012)	0.384 (0.071)	0.160	0.348* (0.035)	
	Grand Total	433.882* (431.886)	71.165* (70.932)	362.364* (360.80)	149.97	213.128* (211.56)	41.57

Note: 1995 estimates are projected to 2003

* Total Replenishable Groundwater Resource of the country was estimated to be 433.68 BCM. However, as per decision taken in 1995, the agreed figure of 432 BCM is retained as rounded off figure of 431.88 BCM. The discrepancy actually has crept in due to inclusion of figures in respect of Mizoram, Sikkim and UT of Andaman & Nicobar at a later stage.

Groundwater Quality

The chemical quality of groundwater plays a vital role in its various uses. The geochemical and geothermal characteristics of groundwater are dependent on the interplay of meteorological, geological, pedological and topographical conditions, which have a direct bearing on the natural concentration of salts in groundwater. The chemical quality of groundwater occurring within shallow depths varies widely in the country because of human interference. Generally, the chemical constituents that affect the potability of groundwater, are within the permissible range in major parts of the country. In places, the groundwater has high geo-genic concentration of fluoride, nitrate, iron, arsenic, salinity and dissolved salts, which restricts its use for various purposes. The district wise problems of contamination of groundwater due to various contaminants are given in Table 3. The chemical quality of groundwater has been affected through domestic, agricultural and industrial pollution. Intensification of agricultural cultivation has lead to significant deterioration in groundwater quality in some areas. The principal problems are the leaching of nutrients, and pesticides, and increasing salinity in the more arid or coastal environments.

The subsoil and the underlying rock formations can eliminate or attenuate many water pollutants by natural, physical, chemical and biological processes. But this natural capacity does not extend to all types of water pollutants and varies widely in effectiveness under different hydro-geological conditions. Serious pollution of groundwater occurs when pollutants are discharged to, deposited on, or leached from the land surface, at rates significantly exceeding the natural attenuation capacity. This is occurring widely as a result of both the indiscriminate disposal of liquid effluents and solid wastes from urban development with inadequate sanitation arrangements, and of uncontrolled leakage of stored chemicals into the ground from industrial activities.

In many coastal areas, such as near Chennai and also in small islands, over-exploitation is leading to the intrusion of saltwater inland, causing effectively irreversible deterioration of groundwater resources.

Groundwater pollution is insidious and expensive; insidious because it takes many years to show its full effect in the quality of water pumped from deep wells; expensive because, by the time it is detected, the cost of remediation of polluted aquifers becomes extremely high. Indeed, restoration to drinking water standards is often practically impossible.

Groundwater Issues

Developing and managing this resource in a sustainable way poses many challenges. The major concerns of groundwater development and management in India are: low development in prospective areas and high rate of groundwater development leading to groundwater depletion, groundwater quality problem due to intrinsic properties of the rock formations and domestic, agricultural and industrial pollution, in other areas.

Table 3. Statewise details of contamination of groundwater in some areas of the districts due to various contaminants

S. No.	State	Salinity	Iron	Fluoride	Nitrate	Arsenic	Heavy metals
1.	Andhra Pradesh	East Godavari, West Godavari, Krishna, Guntur, Prakasam	—	Prakasam, Nellore, Anantapur, Nalgonda, Rangareddy, Adilabad	Vishakhapatnam, East Godavari, Krishna, Prakasam, Nellore, Chittoor, Anantapur, Cuddapah, Kurnool, Mehboob-nagar, Rangareddy, Medak, Adilabad, Nalgonda, Khammam.	—	Anantapur, Mehboobnagar, Prakasam, Visakhapatnam, Cuddapah, Nalgonda.
2.	Assam	—	Northern bank of Brahmaputra	Nagaon, Karbi Anglong	—	—	Digboi
3.	Bihar	Begusarai	Champaran, Muzaffarpur, Gaya, Munger, Deoghar, Madhubani, Patna, Palamau, Nalanda, Nawada, Banka	Giridih, Jamui, Dhanbad	Palamau, Gaya, Patna, Nalanda, Nawada, Bhagalpur, Sahebgunj, Banka	—	Dhanbad, Muzaffarpur, Begusarai.
4.	Gujarat	Banaskantha, Junagarh, Bharauch, Surat, Mehsana, Ahmedabad, Surendranagar, Kheda, Jamnagar	—	Kachch, Surendranagar, Rajkot, Ahmedabad, Mehsana, Banaskantha, Sabarkantha.	—	—	—
5.	Haryana	Sonepat, Rohtak, Hissar, Sirsa, Faridabad, Jind, Gurgaon, Bhiwani, Mahendragarh	—	Rohtak, Jind, Hissar, Bhiwani, Mahendra-garh, Faridabad	Ambala, Sonepat, Jind, Gurgaon, Faridabad, Hissar, Sirsa, Karnal, Kurukshetra, Rohtak, Bhiwani, Mahendragarh	—	Faridabad
6.	Himachal Pradesh	—	—	—	Kulu, Solan, Una	—	Purwanoo, Kalaamb

(*Contd.*)

Table 3. (*Contd.*)

S. No.	State	Salinity	Iron	Fluoride	Nitrate	Arsenic	Heavy metals
7.	Karnataka	Bijapur, Belgaum, Raichur, Bellary, Dharwar	—	Tumkur, Kolar, Bangalore, Gulbarga, Bellary, Raichur	—	—	Bhadrawati
8.	Kerala	Ernakulam, Trichur, Alleppey	—	Palghat	—	—	—
9.	Madhya Pradesh & Chhatisgarh	Gwalior, Bhind, Morena, Jhabua, Khargaon, Dhar, Shivpuri, Shajapur, Guna, Mandsor, Ujjain	—	Bhind, Moerana, Guna, Jhabua, Chhindwara, Seoni, Mandla, Raipur, Vidisha	Sehore	Rajnand-gaon	Bastar, Korba, Ratlam, Nagda
10.	Maharashtra	Amaravati, Akola.	—	Bhandara, Chandrapur, Nanded, Aurangabad	Thane, Jalna, Beed, Nanded, Latur, Osmanabad, Solapur, Satara, Sangli, Kolhapur, Dhule, Jalgaon, Aurangabad, Ahmednagar, Pune, Buldana, Amravati, Akola, Nagpur, Wardha, Bhandara, Chandrapur, Gadchiroli	—	—
11.	Orissa	Cuttack, Baleswar, Puri	Parts of Coastal Orissa	Bolangir	—	—	Angul, Talcher
12.	Punjab	Bhatinda, Sangrur, Faridkot, Firozpur.	—	Ludhiana, Faridkot, Bhatinda, Sangrur, Jalandhar, Amritsar.	Patiala, Faridkot, Firozpur, Sangrur, Bhatinda.	—	Ludhiana, Mandi Gobindgarh.
13.	Rajasthan	Bharatpur, Jaipur, Nagaur, Jalore, Sirohi, Jodhpur	Bikaner, Alwar, Dungarpur	Barmer, Bikaner, Ganganagar, Jalore, Nagaur, Pali, Sirohi.	Jaipur, Churu, Ganganagar, Bikaner, Jalore, Barmer, Bundi, Swai Madhopur.	—	Pali, Udaipur, Khetri.

(*Contd.*)

Table 3. (*Contd.*)

S. No.	State	Salinity	Iron	Fluoride	Nitrate	Arsenic	Heavymetals
14.	Tamil Nadu	Karaikal, Pondicherry, Nagapattanam, Quide-Millet, Pudukottai, Ramananthapuram, North Arcot Ambedkar, Dharampuri, Salem, Trichy, Coimbatore.	—	Dharampuri, Salem, North Arcot-Ambedkar, Villipuram-Padayatchi, Muthuramalingam, Tiruchirapalli, Pudukottai.	Coimbatore, Periyar, Salem.	—	Manali, North Arcot.
15.	Tripura	—	Dharamnagar, Kauleshaher, Khowai, Ambasa, Amapur and Parts of Agartala Valley	—	—	—	—
16.	Uttar Pradesh	Agra, Mathura, Mainpuri, Banda	—	Bulandshahar, Aligarh, Agra, Unnao, Rae-Bareli	Orai, Jhansi, Lalitpur, Faizabad, Sultanpur, Maharajganj, Gorakhapur, Deoria	Ballia	Singrauli, Basti, Kanpur, Jaunpur, Allahabad, Saharanpur, Aligarh.
17.	West Bengal	—	Midnapore, Howrah, Hooghli, Bankura	Birbhum	Uttar Dinajpur, Malda, Birbhum, Nadia, Midnapur, Howrah, Murshidabad, Purulia	Malda, S&N-24 Paraganas, Nadia, Hoogly, Murshidabad, Bardhaman, Howrah	Durgapur, Howrah, Murshidabad, Nadia.
18.	NCT of Delhi	Najafgarh, Kanjhawala, and Mehrauli Blocks.	—	—	City Shahdara and Mehrauli Blocks.	—	Alipur, Kanjhawala, Najafgarh, Mehrauli City and Shahdara Blocks.

While developing groundwater resources promises to help alleviate poverty in many areas, the most formidable groundwater challenge is to attain the sustainable use and management of groundwater in areas where the resource is under threat. The depletion of groundwater is becoming a major problem in many parts of the country. Groundwater overdraft has many negative consequences associated with it. The ultimate impact of groundwater depletion and water quality deterioration is on the health of large sections of rural population that depend directly on wells as their only source of drinking water supply. Depleting water tables is causing the drilling of deeper wells and an ever-increasing cost of tapping these aquifers.

Developmental Issues in Indo-Ganges-Brahmaputra Basin

The groundwater resource is not evenly distributed throughout the country. Several regions in the country have a good repository of groundwater, which are yet to be tapped. The most significant is the Indo-Gangetic-Bramhaputra basin that is bestowed with about 211 BCM of annual groundwater recharge, which is almost 50 percent of the total potential of the country. It also has a vast in-storage groundwater reserve. The groundwater development in this belt at a low level leaves a good scope for further development.

Developmental Issues in Punjab and Haryana

The success of the Green Revolution in Punjab and Haryana brought with itself the adverse impact on the groundwater regime in the form of over draft. The effect is so pronounced that out of 36 districts in these two states, 25 districts have areas where decline in groundwater levels have set in.

Developmental Issues in Rajasthan

In the western arid sector of the country, in Rajasthan, there is little natural recharge to the groundwater regime. In sharp contrast, the INGP command area faces the problem of land degradation due to water logging and consequent soil salinity. The problems of meteorological and agricultural droughts and land degradation due to water logging and soil salinity are required to be addressed on priority.

Developmental Issues in Deltaic and Coastal Sediments

The unconsolidated deltaic and coastal sediments along India's coastline contain thick and regionally extensive aquifers that have good yield potential and can sustain deep, moderate to high capacity tube wells. Although enormous fresh groundwater resources are identified in these areas all along the coast, its uncontrolled development suffers heavily from inherent salinity hazards. Coastal parts of Gujarat, Tamil Nadu and Andhra Pradesh are already suffering from the problem of salinity ingress.

Developmental Issues in Peninsular States

The peninsular states of Maharashtra, Andhra Pradesh, Karnataka, Tamil Nadu and Kerala are characterized by hard rock formations, which lack primary porosity and have extreme heterogeneity and restricted storage capabilities of groundwater. Occurrence of groundwater is limited to areas where the structure of the rock formations favors storage and transmission of groundwater.

Groundwater Ownership Issues

A private individual investing his own resource can construct wells of any design, installing pumps of any capacity. Under the Land Easement Act of 1882, groundwater is considered an easement connected to land. Ownership of groundwater thus falls to the landowner who is free to extract and use it as he/she deems fit. When the Easement Act was promulgated, the popular and prevalent means of groundwater withdrawal were through dug wells. With the advent of electrically powered pumps and advanced drilling methods, the situation has changed drastically. The demand for groundwater has increased manifold. Between 1951 and 1992, dug wells increased from 3.86 million to 10.12 million, shallow tube wells from 3000 to 5.38 million, public tube wells from 0 to 68,000, electric pumps from zero to 9.34 million, and diesel pumps from 66,000 to 4.59 million. In the VIII plan, a further addition of 1.71 million dug wells, 1.67 million shallow tube wells; 114,000 deep tube wells 2.02 million electric pumps and 420,000 diesel pumps took place. Exclusive rights over water have resulted in not only exploitation of needy farmers but also that of the groundwater resources.

Management Options

Presently, groundwater management rather than development is the major challenge that is being faced. There are certain strong reasons suggesting the need for such a shift:

- The private sector predominance in this sector is strong.
- The expansion of groundwater management problems across many parts of the country at a rapid rate

With the sustainable limits of groundwater extraction being approached, competition between agriculture and other uses are intensifying. Naturally, allocation problems are particularly complicated in areas where overdraft, quality and pollution problems exist. In some areas, current levels of use are being maintained by mining groundwater resources. In these areas, cutbacks in extraction are essential, as are measures to dramatically increase the productivity per unit of water. In all areas, the challenge is to maintain extraction within sustainable limits.

The various management options to explore are:

- Legal framework regarding use of groundwater.
- Community support for this legal framework since the majority of the groundwater structures in the country are privately owned. This would lead to effective implementation of the regulations since there will be no opposition from the local populace.

- Development of water markets, if established within effective rights, institutional and regulatory framework could play a major role in providing water to various use sectors.
- Effective co-ordination and communication between various agencies dealing with various aspects of groundwater.
- Groundwater being in the dynamic state requires to be monitored on a continuous basis for quantity and quality. Detailed and precise studies using modern tools would lead to more accurate data generations, which shall ultimately result in a more accurate assessment of groundwater resources of the country.
- It should also include artificial recharge, conservation, conjunctive use, and land use planning as per the availability of water and taking appropriate measures to avoid pollution.
- The provision of free or subsidized power in the agriculture sector needs to be given a fresh look. Suitable cost of electricity is to be decided so that no misuse/ overuse of power takes place.

Measures for Attaining Sustainability of Groundwater Development

Recently, several initiatives have been taken to augment the groundwater supplies and ensure its sustainable utilization. Some of the important measures include the following:

Artificial Recharge

Harnessing surplus monsoon flows to recharge the aquifer system could, in principle, augment groundwater resources. According to a study conducted by the Central Groundwater Board, about 214 BCM of surplus monsoon runoff in 20 major river basins in the country could be stored as groundwater, out of which 160 BCM is considered to be retrievable. In the minor irrigation sector, percolation tanks, *nala* bunds, gully plugs, check dams, sub-surface dykes are some of the suitable structures, which can be effectively used, depending on the hydrogeological setting, to augment groundwater resources and also provide irrigation water to needy farmers. Stress should also be laid on conjunctive use of surface and groundwater in the irrigated command areas. This could boost the irrigation facility in the tail end areas.

Model Bill

In an effort to control and regulate the development of groundwater, the Ministry of Water Resources circulated a Model Bill to the states in 1970, which was again re-circulated in 1992 and 1996. So far, six states/union territories, namely Andhra Pradesh, Goa, Tamil Nadu, Kerala, Lakshadweep and Pondicherry have enacted the legislation. In two states, namely Gujarat and Maharashtra, the bill has been passed but not enacted. Action on the model bill has been initiated in 16 states/union territories.

Constitution of Central Groundwater Authority

Further, for the purpose of control and regulation of groundwater development, the Central Groundwater Board was constituted as the Central Groundwater Authority in January 1997 under the Environment (Protection) Act 1986. The authority has taken initiative in declaring areas as protected areas from the point of view of groundwater overexploitation. The other activities of the Authority include monitoring of groundwater contamination, registration of agencies involved in construction of wells, registration of persons/agencies engaged in sale and supply of mineral water from groundwater, clearance to groundwater-based projects, conducting mass awareness programs and training in rain water harvesting.

The Central Groundwater Authority has declared 11 priority areas for groundwater regulation and also notified 32 areas for registration of groundwater abstraction structures in the states of Rajasthan, Madhya Pradesh, Punjab, Haryana and Andhra Pradesh.

Amendment of Building Byelaws

In urban areas the Government of India has amended building byelaws and made rainwater harvesting, as a means of artificial recharge, mandatory. So far, Tamil Nadu, Delhi, Haryana have taken action. Other states are in the process of amending the building byelaws to make rainwater harvesting mandatory in the special class of buildings.

Correcting Sub-optimal Development of Groundwater

Development of groundwater is sub-optimal in certain parts of the country causing rejected recharge. The low development of groundwater is attributed to fragmented land holdings, lack of efforts in public funding for construction and energizing of wells/ tube wells. A scheme has been formulated to address this issue of inadequate development of groundwater resource. The scheme is proposed to be implemented throughout the country except the states of Haryana, Punjab, Rajasthan and Union Territories of Chandigarh, Delhi, Lakshadweep, Daman and Diu, where problems of either continuously declining groundwater level or that of quality deterioration exists. Under the scheme, stress would be laid on the development of groundwater in the Ganga-Brahmaputra basin where there is ample scope of development of groundwater. It is proposed to construct 2,680,100 structures at a cost of Rs. 153 billion. The additional irrigation potential likely to be created has been assessed at about 5.24 M ha.

Spring Development

Hard rocks mostly underlie the mountainous regions of northern and northeastern India. The total annual rainfall in these areas is generally more than 2000 mm. As the areas have high slopes, the run-off is generally very high. Further, absence of widespread, continuous aquifers has reduced the groundwater storage to a bare minimum. The major source of groundwater in such areas is springs, which have discharges ranging from 0.1 to 30 lps. These springs provide excellent quality of water and it is essential to take up studies regarding the occurrence, areas of recharge / discharge, movement of water through these springs to enhance the availability of sustainable drinking water supplies to the populace living in these high altitude areas.

Water resources development and management need to be planned in an integrated manner taking into consideration long term as well as short term planning needs. They need to incorporate environmental, economic and social considerations based on the principles of sustainability. An integrated groundwater development and management plan envisaging rational and efficient utilization of regional groundwater system requires a reliable data base, modeling tools to describe the regional flow pattern, proper definition of goals and related criteria and a monitoring network for groundwater flow and groundwater pumpage.

National Blueprint for Recharging Groundwater Resources of India

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Abstract

Post-independent India has witnessed a phenomenal development of its groundwater resources, which, has resulted in deleterious effect in terms of steep decline in groundwater levels, dwindling yield, drying up of wells, and water quality deterioration. The challenge can be effectively met only by taking up programs of artificial recharge to groundwater in a big way throughout the country. The key to success of such programs rests in complete understanding of the hydrogeological situations of the area, and appropriate siting and designs of artificial recharge structures. The paper deals with the efforts made by Central Ground Water Board in the direction of providing scientific base for artificial recharge of groundwater and rainwater harvesting. During the VIIIth and IXth Five Year Plan periods, states implemented various demonstrative schemes throughout the country to create models for their replication under similar hydrogeological situations. The paper further elucidates the master plan for artificial recharge to ground water in India which aims at recharging surplus runoff of about 36.4 billion cubic meters (BCM) in an area of about 0.45 million square kilometers (sq. km.), identified in various parts of the country experiencing a sharp decline of ground water levels.

Challenges for Groundwater Development

The ubiquitous availability of groundwater, coupled with technological advancement in its extraction, institutional support, and deemed considered ownership of groundwater as easement to land has led to quantum leap in the groundwater development in India during last five decades. Even though, the ever increasing dependence on groundwater has ensured country's food security, and fulfilled other socio-economic needs, its over-exploitation at places has led to dwindling sustainability of this precious natural resource with adverse environmental consequences. The serious manifestation of over-exploitation of ground-water resources is evident from the fact that over-exploited and dark blocks in the country have increased from 250 in 1985 to 1089 in 2004, besides recording of steep decline in ground water levels in 300 districts over the years. In areas of inland salinity and coastal regions fresh water aquifers are under persistent threat by ingress of saline water through up-coning and seawater intrusion.

The challenges faced to mitigate the impact of over exploitation of groundwater need a sound groundwater management policy on scientific considerations. The stand alone regulatory measures though may endorse some positive impact, but holistically, various measures are required to augment the available groundwater resources. It also needs adequate level of people's participation, as this can result in positive impact from long-term perspective in minimizing the adverse effects of ground water over exploitation.

Artificial Recharge of Groundwater - An Urgent Need

Natural replenishment of groundwater storage is slow, and is unable to keep pace with the excessive exploitation of groundwater. With increasing urbanization, the land area for natural rainwater recharge is also shrinking and large unutilized run-off carries pollution to the water bodies. Artificial recharge to groundwater aims at augmentation of the groundwater storage by modifying the natural movement of surface water, utilizing suitable civil construction techniques to increase the seepage rate exceeding that under natural conditions of replenishment. The rainfall occurrence in India is limited to about three months and ranges from about 10 to 100 rainy days. The natural recharge is restricted to this period only. The artificial recharge techniques aim at increasing the recharge period in the post-monsoon for about three (3) months to provide additional recharge. This would result in providing sustainability to groundwater development.

In hilly areas, even though the rainfall is high, scarcity of water is felt in post-monsoon season. Due to steep gradients, a large quantity of water flows out to low lying areas as surface runoff. Springs are the major source of water in hilly areas that gets depleted after monsoon. There is a need to provide sustainability to these springs. Small surface storages above the spring level are effective in providing additional recharge and sustain the spring flow for a longer period.

Most of the urban areas in the country are facing water scarcity. The dependence on groundwater has increased many-fold, and the natural recharge to groundwater has decreased due to increased buildings and paved areas. Rooftop rainwater harvesting, which involves the collection of rainwater from the roof of the buildings and its storage in surface tanks or recharge to sub-surface aquifer, can play an important role in conservation of water. Thus, the need for artificial recharge of groundwater is beyond doubt and is the most powerful management strategy available, to face the challenge of fast depletion in groundwater storages.

Government Initiatives

The government of India has initiated several policy measures for artificial recharge of groundwater. These policy measures include experimental studies during the VIIIth and IXth Five Year Plan (FYP) and preparing a master plan for artificial recharge of groundwater. The Central Ground Water Board (CGWB), under the Ministry of Water Resources, Government of India has played a crucial role in initiating artificial recharge in the country and propagating the message to the state governments. CGWB has also involved different public stakeholders including civil society organizations through mass awareness, published and electronic media programs, trainings, and seminars. However, for success of this program, it requires scientific approach, which has been provided by CGWB. Necessary literature in the form of manuals and guides on artificial recharge to groundwater were issued. These documents include detailed technical aspects related to site selection for different types of artificial recharge structures, their suitability to various hydrological and climatic conditions. CGWB undertook demonstration schemes under central sector program on "Study of Recharge to Groundwater" during the VIIIth and IXth Five Year Plan (FYP). These schemes implemented in co-ordination with the state government, with the objective of dissemination of technical know-how to the state government and other agencies, for successful implementation of the methodology elsewhere in the country under similar hydrogeological set up.

During the VIIIth FYP twenty-four projects were taken up mainly in the states of Maharashatra, Karnataka, Delhi, Chandigarh, Madhya Pradesh, Kerala and Tamil Nadu, and 62 artificial recharge structures such as percolation tank, check dam, sub-surface dyke, recharge shaft, recharge wells, roof-top rainwater harvesting systems were constructed and their impact on groundwater regime was evaluated. The expenditure under the scheme as Rs. 32.3 million.

In the IXth FYP, 165 projects, which involved, construction of more than 670 artificial recharge structures in 27 States and Union Territories (UTs) were completed. The efficacies of constructed recharge structures have been evaluated. The projects have been taken up in close coordination with the state government departments who have taken up civil work on cost deposit basis. The expenditure under the scheme was Rs. 333.1 million. Table 1 lists the findings of the impact assessment carried out in some of the completed schemes. These schemes have not only helped in creating awareness for artificial recharge to groundwater and rainwater harvesting but are also expected to contribute towards controlling decline in groundwater levels. From a long term perspective these additional recharge will ensure long-term sustainability of groundwater structures by reducing pump lift and energy consumption.

Master Plan for Artificial Recharge to Ground Water

On the basis of experience gained through implementation of the pilot schemes, CGWB has prepared a "Master Plan for Artificial Recharge to Groundwater in India", bringing the areas for artificial recharge to groundwater reservoir, wherein schemes need to be implemented as s top-most priority to ameliorate the water scarcity problems. A total area of 0.45 million sq. km was identified in the country, which needed artificial recharge of groundwater. This excludes the hilly terrain of Jammu and Kashmir (J&K), Himachal Pradesh, Uttranchal, North Eastern (NE) states and arid regions of Western India and Islands. It is estimated that annually about 3.6 billion cubic meter (BCM) of surplus run-off can be recharged to augment the groundwater. In rural areas, techniques of artificial recharge by modification of natural movement of surface water through suitable civil structures such as percolation tanks, check dams, *nala* (small streams) bunds, gully plugs, gabion

Table 1. Impact assessment of artificial recharge projects under central sector scheme of "Study of recharge to ground water" during VIII & IX plan

Sl. No.	State	Number of schemes assessed	Artificial recharge structures	Impact Assessment
1.	Andhra Pradesh	6	Percolation tanks	4500-5900 m^3 runoff water recharged/annum
		3	Check dams	1000-1250 m^3 runoff water recharged/annum
		1	Combination of recharge pits and lateral shafts	370 m^3 runoff water harvested/ annum
2.	Arunachal Pradesh	1	Roof top rainwater harvesting	7000 m^3 runoff water harvested/ annum
3.	Assam	1	Roof top rainwater harvesting	5500 m^3 runoff water harvested/ annum
4.	Bihar	1	Roof top rainwater harvesting	4700 m^3 runoff water harvested/ annum
5.	Chandigarh	6	Roof top rainwater harvesting	1400-13,000 m^3 runoff water recharged/ annum
		1	Rainwater harvesting through roof top & pavement catchments	3.45 M m^3 runoff water recharged/ annum 0.95M m^3 rainwater runoff recharged/ annum
		1	Recharge trenches	
6.	Gujarat	3	Rainwater harvesting through roof top & pavement catchments	11000-450000 m^3 runoff water recharged/ annum
7.	Haryana	1	Roof top rain water harvesting	2350 m^3 runoff water recharged/ annum
		1	Combination of recharge shafts and injections wells	0.35 M m^3 runoff water recharged in one year. Declining rate reduced from 1.175 m/yr to 0.25 m/yr
8.	Himachal Pradesh	3	Check dams	0.12-2.1M m^3 runoff water recharged/ annum
9.	Jammu & Kashmir	2	Roof top rain water harvesting	3000-12000 m^3 runoffwater harvested/ annum
10.	Jahrkand	1	Roof top rain water-harvesting	4500 m^3 runoffwater recharged/ annum
11.	Karnataka	1	Combination of percolationtanks, watershed structures, recharge wells, rooft oprain water harvesting	2-3.5 m rise in water levels and 9-16 ha area benefitted from percolation tanks 0.86 M m^3 water recharged through recharge well. 3-5 m rise in groundwater levels through watershed structures. 530 m^3 recharged from roof top rain waterharvesting
12.	Kerala	1	Sub-surface dyke	Augmented 5000 m^3 of groundwater in upstream side with 2 m rise in groundwater levels

(*Contd.*)

Table 1. (*Contd.*)

Sl. No.	State	Number of schemes assessed	Artificial recharge structures	Impact Assessment
		1	Recharge wells	2800 m^3 runoff water recharged/ annum
		3	Percolation tanks	2000-15000 m^3 runoff water recharged/ annum
		1	Tidal regulator	4000 m^3 runoff water conserved and a difference of 1.5 m was observed in upstream and downstream water level.
		1	Check dam	30,000 m^3 runoffwater recharged/ annum
13.	Lakshdweep	1	Rooftop rainwater harvesting	300 m^3 rainwater harvested/ annum
14.	Madhya Pradesh	4111	Sub-surface dykes	Rise in water level in dugwells in the range of 0.80-3.80 m and 6-12 m in handpumps have been observed
			Percolation tanks	Rise in ground water levels by 1-4 m in command areas downstream of tanks has been observed.
			Rooftop rainwater harvesting (1000 houses)	More than 0.2 M m^3 runoff water recharged/ annum
			Combination of sub-surface dykes and check dams	Rise in water levels in existing tube wells in upstream area by 0.3 m to2.0 m has been observed.
15.	Maharashatra	2	Roof top rain water harvesting system	196-280 m^3 runoffwater recharged/annum
		1	Combination of percolationtanks and check dams	Benefitted area-about 60 to 120 ha/ percolation tank and 3 to 15 ha per checkdam, water level rise- upto 1.5 m
		1	Percolation tanks, recharge Shafts, dugwell recharge	Benefited area-400-500 ha around the scheme
16.	Meghalaya	1	Roof top rainwater harvesting	6800 m^3 runoff water harvested/annum
17.	Mizoram	1	Roof top rain water harvesting	50,000 m^3 runoffwater harvested/ annum
18.	Nagaland	2	Roof top rainwater harvesting	3700-12,800 m^3 runoff water harvested / annum
19.	NCT Delhi	2	Check dams	Water levels have risen upto 2.55 m in the vicinity of check dams and area benefited is upto 30 ha from each check dam.

(*Contd.*)

Table 1. (*Contd.*)

Sl. No.	State	Number of schemes assessed	Artificial recharge structures	Impact Assessment
		7	Roof top rainwater harvesting	800-5000 m^3 runoff water recharged / annum
		8	Rainwater harvesting through rooftop and pavement catchments	8500-20,000 m^3 runoff water recharged/ annum
20.	Orissa	1	Rainwater harvesting through rooftop & pavement catchments	19,000 m^3 runoff water recharged/ annum
21.	Punjab	13121	Rooftop rainwater harvesting	500 m^3 runoff water recharged/ annum
			Recharge wells Trenches	0.9-1.55 M m^3 runoff water recharged/annum
			Combination of vertical shafts, injection wells and recharge trenches	Recharge of 0.17 M m^3 runoff water caused average rise of 0.25 m in groundwater levels around the scheme area
			Combination of recharge shafts and injection wells	14,400 m^3 runoff water recharged/ annum Average rise in water level of 0.32-0.70 m has beenobserved.
22.	Rajasthan	1123	Check dams	88,000 m^3 runoff water recharged/ annum, water level rise- 0.65 m
			Roof top rain water harvesting	350-2800 m^3 runoffwater recharged/ annum
			Sub-surface barriers	2000-11500 m^3 runoff water recharged/annum, water level rise from 0.25 to 0.60 m
23.	Tamil Nadu	171	Sub-surface dyke	39.25 ha benefited
			Percolation tanks	10,000-2,25,000 m^3 runoff water recharged / annum
			Rooftop rain water harvesting	3700 m^3 runoff water recharged/ annum
24.	Uttar Pradesh	5	Rooftop rainwater harvesting	350-1100 m^3 runoff water recharged in one year
25.	West Bengal	11	Combination of farm ponds, *nala* bunds, sub-surface dykes	Water level rise of 0.15 m observed.
			Sub-surface dykes	Rise in water levels by 0.45 m observed

structures and sub-surface techniques of recharge shaft and well recharge have been recommended. Provision to conserve groundwater flows through groundwater dams has also been made in some states. The Master Plan envisages construction of 225,000 artificial recharge structures in rural areas. The break-up includes 37,000 percolation tanks, 110,000 check dams, nala bunds, cement plugs, weirs, anicuts;

48,000 rechrge shafts, dug well recharge, around 1,000 revival of ponds and 26,000 gully plugs, gabion structures. In J&K, HP, Uttranchal, NE states and Sikkim emphasis has been given for spring development, and 2700 springs are proposed for augmentation and development. The Master Plan also envisages construction of 3.7 million rainwater harvesting systems in urban roof-top and pavement surplus monsoon run-off. Total cost of the implementation of master plan is Rs. 245 billion. The state wise feasibility and cost estimates are given in Table 2.

Table 2. State wise feasibility and cost estimates of artificial recharge structures in India

Sl. No.	Name of state	Area identified for artificial recharge (sq. km)	Quantity of surface water to be recharged (MCM)	Type and number of artificial recharge structures	Cost (Rs. billion)
1.	Andhra Pradesh	65333	1095	3800 Percolation tanks 11167 Check dams Rainwater harvesting in urban area	16.97
2.	Bihar & Jharkhand	4082	1120	2695 Percolation tanks 9483 Nala bunds 1630 Recharge shafts	9.74
3.	Chattisgarh	11706	258	648 Percolation tank 2151 Gravity Head/ Recharge shafts 7740 Gully plugs, Gabion Structures	2.74
4.	Delhi	693	444	23 Percolation tanks 23 Existing dug wells 10 Nala bunds 2496 Roof top rain water harvesting	2.57
5.	Goa	3701	529	1410 Check dam/KT weirs 10,000 Roof top rain water structure	0.73
6.	Gujarat	64264	1408	4942 Percolation tanks with recharge tube wells 13210 Check dams, Rainwater harvesting (4.5 lakh houses)	16.05
7.	Haryana	16120	685	15928 Recharge shafts and recharge trenches	3.32
8.	Himachal Pradesh	—	149	1000 Sub surface dykes 500 Check dams 300 Revival of ponds 500 Revival of springs 2000 Roof top harvesting structures	46.55
9.	Jammu & Kashmir	—	161	1500 Sub surface dykes 336 Revival of *Kandi* ponds Roof top harvesting (0.15 M houses)	24.65

(*Contd.*)

Table 2. (*Contd.*)

Sl. No.	Name of state	Area identified for artificial recharge (sq. km)	Quantity of surface water to be recharged (MCM)	Type and number of artificial recharge structures	Cost (Rs. billion)
10.	Karnataka	36710	2065	1040 Sub surface dams 5160 Percolation tanks/desilting of old tanks 17182 Check dams 0.83 M Roof top rainwater harvesting with filter bed.	17.32
11.	Kerala	4650	1078	4312 Check dams 7181 Sub surface dykes 10780 Gully plugs 10780 Nala bunds Rooftop rainwater harvesting (0.07 M houses) Runoff water harvesting (1200 structures)	12.78
12.	Madhya pradesh	36335	2320	5302 Percolation tanks 20198 Nala bunds/ Cement plug/Check dams 23181 Gravity head/Dug wells/ Tubewells/ recharge shafts 69598 Gully plugs, Gabian structures	21.53
13.	Maharashatra	65267	2318	8108 Percolation tanks 16598 Cement Plugs 2300 Recharge shafts, Urban schemes of roof top rain water harvesting (0.88 M houses) 3500 Run off harvesting structures	25.62
14.	Arunachal Pradesh	—	—	500 Check dams 1000 Weirs 1000 Gabian structures 480 Roof top harvesting 300 Development of springs	0.94
15.	Assam	—	—	250 Check dams 500 Weirs 1000 Gabian structures 600 Roof top harvesting 250 Development of springs	0.59
16.	Manipur	—	—	300 Check dams 500 Weirs 500 Gabian structures 300 Roof top harvesting 150 Development of springs	0.53
17.	Meghalaya	—	—	300 Check dams 600 Weirs 600 Gabian structures 300 Roof top harvesting 200 Development of spring	0.58

(*Contd.*)

Table 2. (*Contd.*)

Sl. No.	Name of state	Area identified for artificial recharge (sq. km)	Quantity of surface water to be recharged (MCM)	Type and number of artificial recharge structures	Cost (Rs. billion)
18.	Mizoram	—	—	500 Check dams 1000 Weirs 1000 Gabian structures 300 Roof top harvesting 200 Development of spring	0.87
19.	Nagaland	—	—	500 Check dams 1000 Weirs 1000 Gabian structures 300 Roof top harvesting 200 Development of spring	0.87
20.	Tripura	—	—	300 Check dams 500 Weirs 1000 Gabian structures 240 Roof top harvesting 100 Development of spring	0.51
21.	Orissa	8095	406	569 Percolation tanks 761 Converted percolation tanks 698 Sub surface dykes 809 Nala contour bunds 679 Check dam weir 1981 Water spreading/flooding 668 Induced recharge 334 Recharge shafts Roof top harvesting (0.1M houses)	5.14
22.	Punjab	22750	1200	40030 Recharge shafts and recharge trenches 12800 Roof top harvesting structures in urban areas	5.28
23.	Rajasthan	39120	861	3228 Percolation tanks 1291 Anicuts 2871 Recharge shafts Rooftop rainwater harvesting structure (0.4 M houses)	11.40
24.	Sikkim	—	44	2100 Spring development 2500 Cement plugs/nala bunds 5300 Gabian structures 69597 Roof water harvesting	1.73
25.	Tamil Nadu	17292	3597	8612 Percolation ponds 18170 Check dams 0.5 M Rain water harvesting structure	23.86
26.	Uttar Pradesh & Uttranchal	45180	14022	4410 Percolation tanks 12600 Cement plugs (Check dams) 2,12,700 Recharge shafts Roof top rain water harvesting structures (1.0 M)	41.61

(*Contd.*)

Table 2. (*Contd.*)

Sl. No.	Name of state	Area identified for artificial recharge (sq. km)	Quantity of surface water to be recharged (MCM)	Type and number of artificial recharge structures	Cost (Rs. billion)
27.	West Bengal	7500	2664	11200 Percolation tanks with shaft 1054 Nala bunds/Cement plug 1680 Re-excavation of tanks 500 Desiltation of village pond 1000 Spring development 70 Sub surface dykes 1500 Rooftop harvesting for Calcutta & Darjeeling cities	13.41
28.	Andaman & Nicobar	—	3	145 Spring development 270 Cement plugs 38 Percolation tanks 150 Sub surface dykes 2600 Roof top harvesting	0.36
29.	Chandigarh	33	26	597 Recharge shafts, recharge trenches, check dams and Gabian structures	0.06
30.	Dadra & Nagar Haveli	—	—	500 check dams/cement plugs 58 Sub surface dykes 1000 houses rain water harvesting	0.03
31.	Daman & Diu	—	—	100 Nala Bund/check dams 2000 roof top rain water harvesting structures	0.15
32.	Lakshawdeep	—	—	1000 roof top rain water harvesting structures	0.10
33.	Pondicherry	—	—	5 Percolation Tanks 14 Recharge Pit 20 check dams 40 Desilting of dams 10 Nala Bunds 20 Desilting/Recharge wells Rainwater harvesting 10,000 houses	0.122
				Grand Total (Rs*. billion)	244.63

* 1 US$ ~ Rs.45

Based on the findings of 'Master Plan' CGWB proposed a central government sponsored scheme on "Artificial Recharge to Groundwater and Rainwater Harvesting" at estimated cost of Rs. 1.75 billion. The scheme is funded by the central and state government: 75% is the central government share, and, 25% is the contribution from the state government. Beneficiaries will contribute towards operation and maintenance. The scheme is proposed to be implemented during the X^{th} FYP. The scheme will be implemented in identified areas of different states, particularly in: over-exploited and dark blocks, drought prone and water scarcity areas, coastal areas and islands affected by saline water ingress, areas of inland salinity, urban areas showing steep decline in ground water levels and in sub-mountainous, hilly areas of the country. It is proposed to construct 5088 artificial recharge and rainwater harvesting structures on community cluster basis. The proposed scheme will be implemented through state government under the technical guidance of CGWB.

Advisory Council for Rainwater Harvesting

Rainwater harvesting has become an important and frontal management strategy in the country. Ministry of Water Resources is considering a proposal to constitute an advisory council for rainwater harvesting, which will involve not only representatives from Central and State Governments, but also experts from industries,banking sector and NGO's.

Role of Central Ground Water Authority (CGWA) in Promoting Rainwater Harvesting

The campaign for groundwater recharge and water conservation has to be expanded with greater involvement of youth, women, farmers and various policy and opinion makers. In view of inevitable need of public participation in groundwater recharge activities; the Central Groundwater Authority (CGWA) has taken proactive measures such as awareness and capacity building programs in private sector organizations, NGO's, voluntary organizations, institutions, individuals by organizing mass awareness programs and training programs. Till date, 201 mass awareness programs and 130 water management training programs have been conducted by CGWB in various parts of the country. Industrial associations and residential associations have been actively associated in organizing such programmes. Besides this, CGWB has provided free technical designs to various government and private sector organizations, schools, industrial association and road and flyover projects for promotion of rainwater harvesting. In addition to above, awareness activities on rainwater harvesting have been undertaken by CGWA, involving print and electronic media: messages through *Meghdoot Cards*, broadcasting in All India Radio (AIR) and Doordarshan (television). CGWB has also contributed chapters on "Artificial Recharge and Rainwater Harvesting" in the text books of and web pages on "Rainwater Harvesting" in distance learning portals. Moreover, keeping in view of the urgent need to arrest the further decline in groundwater levels in notified areas, efforts were made for mandatory adoption of rainwater harvesting through group housing societies, institutions and schools, hotels, industrial establishments and farm houses located in notified areas.

The constitutional provision, stipulates water as a state subject, and its management is in the prerogative of state governments. It has been an earnest endeavor on part of CGWA to involve and encourage the state governments to take up rainwater harvesting in the respective states. Persuasion is being made with state governments/UTs for inclusion of roof-top rainwater harvesting in building bye-laws. The states of Andhra Pradesh, Gujarat, Haryana, Kerala, NCT Delhi, Maharashatra, Rajasthan, Tamil Nadu and Uttar Pradesh have already made it mandatory for special category of buildings.

Conclusions

The importance of groundwater availability in country's socio-economic development and to meet the environment concerns has remained in the forefront. Though a major headway in government's initiatives has been made for broad identification of nationwide feasible recharge worthy areas vis-à-vis design consideration of groundwater structures in diversified hydrogeological environments through experimental studies, efficacy of such technology needs to be replicated at grass-root level for other areas for micro-level considerations. As urban areas are hotspots of groundwater development activities, it should be the endeavor of groundwater planners to prioritize the recharge activities in these areas, with active involvement of various stakeholders including industries. In rural areas watershed management may remain one of the viable options for groundwater recharge activities.

There is also need to further step up the awareness activities and capacity building program at grass-root level with active people's participation to promote rainwater harvesting in the country.

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Central Groundwater Authority-Past Experience and Future Strategies for Regulating the Development and Utilization of Groundwater in India

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Abstract

Role of groundwater in country's food security and for meeting requirements of domestic and industrial sectors is recognized by all, yet the full implications of its injudicious utilization is understood by only a few. The price to be paid for this rapid development is emerging in the form of increasing areas of water scarcity and fast decline in groundwater levels. Groundwater management is the need of the day to meet various sectoral demands without causing damage to fragile aquifers under stress. Central Groundwater Authority (CGWA) constituted under Environment Protection Act, 1986, under the direction of the Hon'ble Supreme Court of India, is playing its role in regulation and control of groundwater in the country. The paper deals with various activities of CGWA and experiences during their implementation. The positive impact of control is reflected in greater awareness on the need for a judicious management of available resources. Mere regulatory interventions cannot be successful unless the different user groups are fully involved and provide their cooperation and participation. CGWA has played a proactive role in creating awareness about demand side management including artificial recharge of groundwater and rainwater harvesting which has started showing its results as a public movement. The future strategy to effectively manage the fast depleting groundwater resources in the country, envisages constitution of State Groundwater Authorities with technical support from Central Government. At present some movement has started and it is hoped that with adequate level of public awareness and political willingness the need for groundwater governance in the country is realized by not only a few but all to ensure the sustainability of groundwater resources.

Groundwater Scenario

Post independence era in India has witnessed phenomenal growth in utilization and development of groundwater in resources, which are attributed to growing demands of fresh water by various sectoral users and technological advancement in water well drilling. Presently, more than 80% of water supplies for domestic use in rural areas, 50% of water for urban and industrial areas, and more than 50% of irrigation water requirement are being met from groundwater. Groundwater also provides water security during prolonged drought periods. National Commission for Integrated Water Resources Development, 1999 has worked out the gross water requirement for the future use. It has been estimated that 843 billion cubic meter (BCM) of water will be required by 2025 from all sources (High demand scenario). Out of this, about 298 BCM (35.3%) of annual water requirement is to be met from groundwater sources. The groundwater availability in the Indian sub-continent is highly complex due to diversified geological formations, complexity in tectonic framework, climatic dissimilarities and ever changing hydro-chemical environments.

Although the present status of groundwater development in majority of the states is low to moderate, it is significantly high in number of states/ Union Territories (UT) namely, Haryana, Punjab, NCT Delhi, Rajasthan and UT of Chandigarh. Micro-level groundwater assessment at administrative block level carried out by CGWB along with the state governments have identified more groundwater stressed areas, which are presented in Table 1 (see Table 1 of M. Mehta in this volume). Presently, 673 blocks/watersheds of the country are 'Over-exploited' where the groundwater development exceeds its annual replenishable recharge and 425 blocks/ watersheds are 'Dark' or 'Critical' where the groundwater development has reached an alarmingly high level (> 85%). The growing dependency on groundwater resources for sustained irrigation has been acknowledged even in drought years for country's food security since last five decades. The importance of groundwater as dependable sources of water supply by other sectoral users has also been recognized as well. It is implied that with intensification of competing users of groundwater and sustainable limits of groundwater extraction already being reached, allocation problems are bound to advent, particularly in areas where over-exploitation, quality and pollution problems exist. In these areas, regulation in groundwater withdrawals is essential for sustainable development of groundwater resources.

Steps Towards Groundwater Governance

As per the constitutional provisions, 'Water' is a state subject and water resource management is the overall responsibility of the state governments. The complexity of natural occurrence of groundwater in diversified hydrogeological environments, its multifarious importance as socioeconomic commodity, and environmental entity and problems of ownership issue has made the scientific management of groundwater resource a mammoth-challenging task.

A limited control on groundwater over-exploitation are exercised by states through indirect measures, such as, stipulation of spacing criteria between groundwater structures by financial institutions (like NABARD), technical clearances of groundwater development schemes by Ground Water Departments of the concerned states, and, denial of power connections for pump sets among others. However, in absence of adequate administrative measures, affluent users could not be restrained from construction of high capacity deeper wells especially in critical areas, which, adversely effect shallow wells in the neighborhood. Such concerns have also been echoed in National Water Policy, 2002, which lays emphasis on control of over exploitation through effective regulation.

Model Bill for Groundwater Regulation

In order to enable the states to frame and enact legislation for groundwater governance on scientific consideration, Government of India circulated a model bill in 1970 to all states. The provisions of Model Bill included constitution of State Groundwater Authority and the modalities for regulation of groundwater resources. The Model bill was enacted by some of the coastal States: Andhra Pradesh, Goa, Tamil Nadu, Lakshadweep, Kerala and Pondicherry. In majority of the remaining states, the enactment of Model bill is under active consideration. However, for certain states namely, Nagaland, Sikkim, Tripura and UT of Chandigarh, the state Government did not feel the enactment of legislation necessary.

The revision of Model bill is under active consideration by the Ministry of Water Resources (MOWR). A working group has been constituted for reviewing and finalizing the model bill, keeping the provision of National Water Policy, 2002 and rainwater harvesting.

Constitution of Central Groundwater Authority (CGWA)

The alarming decline of groundwater levels in the country due to over-exploitation of groundwater resources led to a Public Interest Litigation (PIL) before the Hon'ble Supreme Court of India in 1996. Subsequently, under the directive of the Court, Central Groundwater Board (CGWB) was constituted as an Authority under Section 3 of the Environment (Protection) Act, 1986 vide notification no. S.O. 38 (E) dated 14.1.97, and subsequent amendments for the purposes of regulation and control of groundwater development and management. The Honorable Court observed that:

" The main object of Constitution of Board as an Authority is the urgent need for regulating the indiscriminate boring and withdrawal of groundwater in the country. …)"

Commensurate with the mandate Central Groundwater Authority is undertaking groundwater governance through regulation and control of groundwater development and management in the country.

Present Activities of Central Groundwater Authority (CGWA)

Regulation of Groundwater Development

Central Groundwater Authority is regulating development of groundwater in some of the critical and over-exploited areas, through concerned district administration heads. It has so far notified eleven critical areas on consideration of over-development of groundwater resources, to protect the fresh water aquifers to meet drinking and domestic requirements. The list of notified areas are given in Table 2.

State administration of the concerned areas have been issued directives under Section 5 of Environment (Protection) Act, 1986, to ensure that no groundwater development is done without prior approval of CGWA. In case of violations, they have been advised to seal the tube well or even seize the drilling equipments. Abstraction of groundwater in these notified areas for sale and supply has also

Table 2. List of notified areas for regulation of groundwater development

Sl. No.	Place	State/ U.T.	Need for regulation	Date of public notice
1.	Municipal Corporation of Faridabad & Ballabgarh	Haryana	Depletion of groundwater resources due to over-exploitation	14.10.98
2.	Union territory of Diu	Diu	Depletion of groundwater resources and seawater ingress due to over exploitation.	17.10.98
3.	Ludhiana City, Ludhiana district.	Punjab	Depletion in groundwater resources due to overexploitation.	8.12.98
4.	Municipal Corpo-ration of Ghaziabad, Ghaziabad District	Uttar Pradesh	Depletion in groundwater resources due to overexploitation	4.4.99
5.	Jhotwara Block, Jaipur district.	Rajasthan	Depletion of groundwater resources due to over exploitation.	24.12.99
6.	South District	NCT, Delhi	Depletion of groundwater resources due to overexploitation	15.08.2000
7.	South West District	NCT, Delhi	Depletion of groundwater resources and upconing of saline groundwater due to overexploitation	15.08.2000
8.	Gandhinagar taluka, District Gandhinagar	Gujarat	Due to limited availability of fresh water, aquifers below 200meters depth notified exclusively for drinking and domestic use.	2.9.2000
9.	Haldia Municipal Area, District East Medinipur	West Bengal	Depletion of groundwater resources and salinity ingress due over-exploitation.	8.9.2000 12.2.2003
10.	Yamuna Flood Plain Area	NCT, Delhi	Due to limited availability of fresh water, Flood plain aquifers notified exclusively for drinking and domestic use.	2.9.2000
11.	Gurgaon town and adjoining industrial areas of Gurgaon district	Haryana	Depletion of groundwater resource due to over-exploitation.	26.12.2000

been banned. In notified areas of Delhi and Haryana, CGWA is directly regulating the groundwater development. CGWA is according limited permission for construction of new tube wells or replacement of existing tube well to government water supplying agencies, institutes, hospitals, embassies etc, to meet their drinking and domestic requirements. District administration is taking action in case of violations, and CGWA if any complaint is received, forwards it to them for action. Directives have also been issued to group housing societies, institutes, hotels, industries, and farmhouses to adopt rainwater-harvesting system in notified area of Delhi, Faridabad, Gurgaon and Ghaziabad.

In addition to above, CGWA has also notified 32 over-exploited areas (Blocks/ taluks) in the country for registration of groundwater structures through the state administration with a view to assess the realistic scenario of groundwater development in these areas for future regulation. Based on the data of registration the reassessment of dynamic and static groundwater resource of the areas will be carried out for these areas for confirmation of status of over exploitation. The list of areas is presented in Table 3.

Table 3. Over-exploited areas in the country for registration of groundwater structures through the state administration

State	Notified Areas
Rajasthan	Pushkar valley, Ajmer district; Behror block, Alwar district; Bhinmal block, Jalore block & Raniwara block, Jalore district; Budhana block, Chirawa block & Surajgarh block Jhunjunu district; Mundwa block, Nagaur district; Dhod block & Shri Madhopur block, Sikar district
Madhya Pradesh	Dhar block & Manawar blocks of Dhar district; Mandsaur block & Sitamau blocks of Mandsaur district; Neemuch block of Neemuch district; Jaora block of Ratlam district, Indore Municipal Corporation
Punjab	Moga-I block & Moga-II block of Moga district; Sangrur block, Mahal Kalan block & Ahmedgarh blocks of Sangrur district.
Haryana	Shahbad block of Kurukshetra district, Nangal Chowdhary block & Namaul block of Mahendergarh district; Samalkha block of Panipat district; Karnal block of Karnal district, Khol block of Rewari district
Andhra Pradesh	Midjil Mandal of Mahabubnagar district, Tirupathi (Rural) Mandal of Chittoor district, Vempalli Mandal of Cuddapah district

Central Groundwater Board (CGWB) is identifying additional over-exploited areas through micro-level studies for registration of groundwater structures.

Clearance to Industries and Projects

CGWA is regulating groundwater withdrawal by industries in over-exploited and dark blocks. A list of such critical areas have been circulated to various statutory organizations like State Pollution Control Boards, Ministry of Environment and Forests, which refer the new industries to CGWA for obtaining approval. The projects referred are examined and technical clearances are accorded by CGWA on case-to-case basis based on recommendations of regional offices of Central Groundwater Board.

Representation of CGWA in the Expert Committees of Ministry of Environment and Forests

Ministry of Environment and Forests (MoEF) has constituted various technical expert committees for environmental appraisal of various categories of developmental projects, under the provisions of Environment Impact Assessment Notification. Based on the recommendation of such committees, environmental clearances are accorded by the Ministry. CGWA is representing two of such committees, (a) Mining projects, and (b) Infrastructure development and miscellaneous projects.

Groundwater Pollution from Geogenic Sources

Based on field-studies by regional offices of CGWB, as well as from other sources such as news items, the incidence of groundwater pollution are being examined by CGWA on case-to-case basis. Depending upon the merit of the individual cases, specific directives are being issued to the state government for taking up suitable action. Arsenic contamination in Bhojpur area,(Bihar) and Balia district (UP) are some of the case examples.

Registration of Persons and Agencies Engaged in Construction of Water Wells

In order to develop database on drilling activities being carried out for regulatory measures, countrywide registration of drilling agencies are being undertaken by CGWA. Such data base not only provide information on current pace of groundwater development scenario, but also decipher micro level site specific information on groundwater availability and technology advancement for development of the same. As a regulatory measure, the drilling agencies have been prohibited to take up the work of construction of water well in the notified areas. They are also required to submit the details of drilling undertaken by them within one month of construction of water wells.

Role of CGWA in Legal Issues

Since inception, the role of CGWA on legal issues have been significant, especially to mention about the Honb'le Supreme Court matter on depletion of groundwater due to mining activities in Aravalli Hills (the matter is under subjudice). CGWA provided necessary technical reports based on spot surveys. CGWA is also rendering active assistance to the Hon'ble Supreme Court, the High Courts and other designated courts on various legal matters concerning water conservation, which includes among others, highway and flyover projects, and protection of water bodies.

Proactive Approaches

Rainwater harvesting is an activity to facilitate groundwater recharge especially in groundwater stressed areas. Public participation is essential for promotion of this activity. Identifying inevitable need for rainwater harvesting, country wide mass awareness programs and training programs on the same are organized by CGWA on regular basis. The objective is to create public awareness about importance of rainwater harvesting in recharging groundwater. Trainings on rainwater harvesting are undertaken for dissemination of cost effective technologies to diverse spectrum of users such as private sector organizations, government agencies, NGO's, educational institutes, and individuals. So far 189 mass awareness programmes, and 120 training programs have been organized. Effective utilization of electronic and print media has also been made to promote this activity. Responses to these programs have been overwhelming, and calls for further stepping up of such activities on large scale with active involvement of various stakeholders. Beside this, CGWB has so far provided technical guidance for 1350 designs for rainwater harvesting to among others: private agencies, government organizations, road and flyover projects, and individuals.

Future Strategies

As stated earlier, task of managing country's vast groundwater resources is a mammoth task and calls for strengthening of the present institutional and legislative framework. It also requires active political support, including people and stakeholders participation to transcribe the techno- legal policies into action. Water being a state subject, its management ultimately has to be accomplished by the states. The groundwater management strategies on long-term perspectives are discussed below:

Groundwater Management in 'Notified Areas' for Regulation of Groundwater Development

In view of past experience and constraints observed, and, in order to ensure more effective implementation of regulatory measures and its monitoring and surveillance in 'notified areas', constitution of an advisory committee at district level is under active consideration. The committee shall be headed by concerned District Collectors /Deputy Commissioner of the notified areas and members drawn from various organizations has been proposed. The Advisory Committees would perform powers and functions of CGWA delegated to them for regulation of groundwater development and management in notified areas under broad framework of techno-legal policies of CGWA. In case State Groundwater Authorities are constituted in the concerned states, they may undertake the regulatory functions including monitoring and surveillance of the same under the policy framework of CGWA.

Declaration of New Areas for Regulation

As stated earlier, to bring in more critical areas under ambit of active regulation and management, CGWA has notified 32 over-exploited areas falling in the state of Andhra Pradesh, Haryana, Madhya Pradesh, Punjab and Rajasthan for registration of groundwater abstraction structures. The registration activity would provide necessary database on realistic estimate of groundwater withdrawals prevailing in these areas. On confirmation of actual number of groundwater structures by the state governments, reassessment of static and dynamic groundwater resources of the critical area would be undertaken by CGWB with state government to ascertain the realistic status of over exploitation vis-a-vis availability of groundwater in the area. Based on this assessment, the areas will be notified for active regulation. On similar lines, more overexploited areas would be identified based on micro-level studies for registration of groundwater structures and regulation.

Conclusions

Groundwater resource development and management need to be planned in an integrated manner taking into consideration long-term as well as short-term planning needs. Integrated groundwater development and management plan, incorporating environmental, economic and social considerations, based on principles of sustainability is necessary at this juncture. Central Groundwater

Authority envisages providing all technical inputs for efficient utilization of groundwater resources in the country in addition to regulating the development of groundwater resources.

Based on the past experience, 'awareness' and 'capacity building' activities have emerged as proactive approaches for management of groundwater resources. Though CGWA has organized a good number of mass awareness and capacity building programme in the country, which has inculcated positive impact on mindsets of different stakeholders including common people, it is felt that the adequate level of awareness is yet to be achieved. This can only be achieved by stepping-up of awareness and capacity building activities, with active involvement of various stakeholders, NGO's, institutes, and industrial and farmer associations in various groundwater management programs.

Understanding Groundwater for Proper Utilization and Management in Nepal

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Abstract

Groundwater resources occur in various natural settings in Nepal due to diversity in its geology, geomorphology and physiography. In the intra-mountain valleys such as Kathmandu, Dang and similar other valleys, groundwater is restricted to well-defined and sometimes isolated basins, whereas groundwater in the relatively flat plains south of the Himalayan mountain ranges, the Terai, forms a part of the larger system operating in the large Indo-Gangetic plains. Almost one half of the country's population is living in the Terai and they depend solely on groundwater for their domestic water needs. Although the available groundwater resource in the Terai has a potential to play a vital role in irrigation to ensure the country's food security and economic growth, its utilization level in irrigation has remained low so far. A contrasting scenario exists in Kathmandu valley, where the resource probably is already being over-exploited. Absence of adequate scientific data essential for proper understanding of the resource system is proving to be a serious set-back for the policy makers and planners in striking a balance between satisfying the water demand and the resource protection in the Kathmandu valley on one hand, and improving the access of the poor farmers, to the abundant groundwater resources in the Terai, on the other hand. Distinct approaches to resource utilization and management are, therefore, essential to address such diverse settings and dissimilar levels of uses. On top of it, discovery of natural arsenic contaminated groundwater in parts of the Indo-Gangetic alluvial plains have added a new challenge for the countries in this region. The socio-economic, infra-structural and policy environment for operation and development of groundwater irrigation in Nepal has some distinctive features, which are different from those of the neighboring countries. Some possible areas of new research and development for proper utilization and management of groundwater resources necessary for sustainable economic development are also discussed.

Introduction

Groundwater occurs in different natural settings in Nepal due to the diversity in geology, geomorphology and physiography. Intra-mountain valleys such as Kathmandu, Dang and other similar valleys have isolated groundwater basins whereas groundwater in the southern *Terai* plain is a part of the larger system in the Gangetic basin. The *Terai* constitutes 23 percent of the country's total area but it is home for over 48 percent of the population. It has abundant groundwater resources, and has fertile soils. This region is the main grain basket of Nepal and has great potential for further agricultural development, necessary for food security and poverty reduction in the country.

Groundwater is a very important water resource for the *Terai*. It is the main source for drinking water supply, and is also becoming increasingly important in the agriculture sector, particularly after the advent of tube well technology in the early 1970's. Since 1980, the Government of Nepal has launched groundwater irrigation development programs in the *Tera*i by providing subsidies in various forms. At the same time, manually operated shallow tube wells have always been the centerpiece of the government's rural water supply development programs. At present, there are already about 800,000 shallow drinking water tube wells in *Terai,* but similar growth has not occurred in the case of irrigation shallow tube wells even after 20 years of government subsidy programs from 1980 to 2000. Compared to a potential of irrigating 612,000 ha, only 206,000 ha of *Terai* land was irrigated with groundwater through about 60,000 shallow tube wells (STWs) and 1,050 deep tube wells (DTWs) in the year 2000. For practical reasons, a shallow tube well is defined in Nepal as a small diameter well (generally of 10 cm diameter) with less than 50 m depth, whereas wells more than 100 m deep are called deep tube wells. The latter has commonly a diameter of at least 15 cm or more.

There are 1,337,000 ha of irrigable agricultural land in the *Terai.* But, only 1,121,000 ha (84 percent) are under irrigation at present, out of this, only 206,000 ha (or 18 percent of the total irrigated area) are under irrigation by groundwater. Studies have shown that annual groundwater recharge in the *Terai* is sufficient to irrigate more than half of its irrigable land (APP, 1995; Kansakar, 1996). The Agricultural Perspective Plan (APP) has placed a high priority on groundwater irrigation, mainly through STWs, for agricultural development in the country. It has planned to irrigate 612,000 ha of *Terai* land by groundwater in a 20-year period (1995-2015). But, the STW growth rate has remained way below this target level. Heavy reliance on economic policy measures without due consideration for social factors is responsible for this failure.

Similar to other countries in this region (like India and Bangladesh), the challenge for Nepal is in increasing groundwater utilization in agriculture for poverty reduction and food security improvement on the one hand, while managing the resource properly on the other hand. Comparatively, Nepal still has a relatively large potential for expanding groundwater use and by proper management Nepal can avoid some of the social, economic and environmental impacts from uncontrolled growth in groundwater exploitation that the neighboring countries are already facing.

Groundwater Management

Groundwater management in Nepal must be viewed from two aspects. One is the resource conservation and protection aspect, and the other is the proper and controlled utilization of the resource.

Resource Conservation and Protection

Traditionally, groundwater resources have been considered as something that will naturally and always be available for human exploitation. The nature of its occurrence makes groundwater a 'common pool' resource, but it is being used commonly as a 'private resource', because it can be exploited independently and privately by anyone who is willing to do so. As a result, it is difficult to regulate or control the exploitation of groundwater. This is more so in the developing countries where law enforcement is generally always weak. Since groundwater occurs beneath the land surface, any harm done to this resource is not visible directly and immediately. Even among the policy makers and the planners, the mentality of 'out of sight – out of mind' works strongly in this case. It is generally too late when the damages become noticeable.

As elsewhere, groundwater in Nepal is also being exploited without any consideration for its management. All the efforts are focused on increasing the exploitation of this resource. Even the scientific investigations are meant for helping intensify this exploitation. Groundwater conservation and management has so far received a 'lip service' only recently, without any concrete programs or mechanisms in place, be it legal, institutional or policy measures. No program has addressed the conservation and sustainability of the resource. Some crucial areas for successful groundwater management in Nepal are discussed here.

Proper Understanding of the Resource

Groundwater resource exploitation will remain sustainable only if the resource utilization level remains in good agreement with resource replenishment, i.e. when conservation rules and measures protect the resource from over-exploitation. But resource conservation is possible only when the groundwater system is well understood.

The annual groundwater recharge or the dynamic reserve depends on the size and nature of the groundwater basin and the climatic conditions. Being a part of the larger Ganges basin and because of ample rainfall/snowmelt confluence, the *Terai* plain is in a good position with respect to renewable groundwater reserves, and has enough scope to expand its utilization. On the other hand, groundwater resources in the mountain valleys have limitations because they are in small and isolated basins. Again, one valley differs from another for their groundwater conditions due to their geologic, physiographic and climatic conditions. To be more specific, a relatively smaller river, the Bagmati, drains Kathmandu valley and it is filled with fine sediments of lacustrine and fluvial origin. Therefore, annual recharge is slow and small. Deep groundwater in the middle of the valley is about 28,000 years old (JICA, 1990). On the other hand, inner *Terai* valleys (e.g. Dang, Deukhuri, and Chitwan) are drained by larger rivers and have coarse fluvial sediment deposits, allowing quick aquifer recharge. But, in Surkhet valley, another valley in the inner *Terai*, has very little groundwater because it contains finer sediments. Therefore, a uniform approach for groundwater development cannot work for all areas. Failure to understand and act according to the specific groundwater conditions has already led to over-exploitation in the Kathmandu valley. It was estimated that 18 MCM of groundwater was being extracted annually against an estimated 5 MCM of annual recharge (CES, 1992). But, there has been no serious attempt to understand the groundwater system in this valley.

Protecting Recharge Areas

Protection of recharge areas has primary importance in groundwater quality and quantity management. The northern part of the *Terai*, known as the *Bhabar* zone, is a narrow belt of an average width of 5 km width along the foot of the Siwalik range. This Bhabar zone is the main recharge area for the multiple aquifer systems occurring in the *Terai*. The Bhabar zone is constituted of coarse grained colluvial and alluvial fan deposits whose sediment sizes decrease gradually towards the south and merges into the main *Terai.* Although direct rainfall recharge is significant all over *Terai*, lateral subsurface recharge from *Bhabar* is important for the deeper confined aquifers.

Earlier a densely forested area, the *Bhabar* zone is presently under rapid human encroachment for various social and economic reasons. The east-west highway, which more or less follows the southern limit of the Bhabar zone, has also contributed extensively to these processes of deforestation and human activity. New settlements and the associated agricultural activities have grown both legally and illegally. Increasingly, modern industrial establishments are also coming up because of the convenience of the highway. The main recharge zone for the *Terai* is thus facing increasing threat from industrial, agricultural and other human activities. Collectively, all of these have consequences on the groundwater recharge and the quality of recharge, which are ultimately important for the health and livelihood of the *Terai* population.

Rapid urbanization has already consumed much of the recharge areas in the Kathmandu valley. Because of its unique geologic construction, the recharge area is limited and groundwater movement is also slow in this basin. Diminishing capture zone and increased human activities in the recharge zone have implications on the groundwater recharge system, which has not received any attention yet.

Protecting Water Quality

Groundwater is the only source of drinking water for the people in the *Terai*. Much of the drinking water supply in Kathmandu valley also comes from this resource. But, quality of water is crucial for this purpose, and hence water quality management is an important aspect of groundwater management.

Shallow groundwater aquifers are mostly used for drinking purposes, but they are also easily polluted because their water originates from unconfined or semi-confined aquifers. Originating in the braided river deposits, the *Terai* aquifers are inter-connected, and hence pollution of one aquifer can contaminate the other easily. Besides anthropogenic contamination, groundwater may also contain natural pollutants. Arsenic is already known to be occurring in the Ganga - Bramaputra - Meghna basin (see Zahid et al., this volume). Shallow aquifers in some parts of the *Terai* have also been found to contain this pollutant (Shrestha et al., 2004, Khadka et al., 2004).

Geology and geomorphology have main control over the occurrence of arsenic in groundwater in the *Terai* (Kansakar, 2004). Shallow aquifers are more susceptible to arsenic contamination, whereas deep aquifers have been found to be generally free from arsenic. But deep tube wells may become contaminated if tube well construction practice is not proper. Arsenic-bearing shallow groundwater may get mixed up with the deep aquifer water in the multiple-screen tube wells and also through gravel pack material in the tube well annular spaces (Bisht et al., 2004). Thus, there is a clear need for groundwater quality management in order that the clean aquifers are protected from contamination and the known groundwater quality problems are adequately addressed in the development programs.

Proper Utilization

Utilization in the Drinking Water Sector

Universally, drinking water use receives precedence over all other uses of any water resource. The Water Resources Act (1992) of Nepal also provides the first priority for drinking water use. But, without suitable water quality, such legal provisions have little meaning, because people will not drink low quality water as long as they have an alternative. Therefore, proper utilization depends much on the quality management.

All of the *Terai* population meets its daily domestic water needs from groundwater. Dug wells have been replaced increasingly by small diameter shallow tube wells (4 cm diameter) since the 1970's. It is estimated that over 800,000 such domestic wells are currently in use in the *Terai* as a whole. In Kathmandu valley also, dug wells and pit basin water spouts (commonly known as *Dhuge Dhara* or *Stone water spouts* were the main sources of domestic water supply before the piped water supply system was introduced in the Kathmandu valley. Since early 1980's, domestic and industrial water demands in the Kathmandu valley are also being met from this resource to a great extent. Nearly 80 percent of groundwater extraction in Kathmandu valley is for domestic purposes and 33.8 MLD or 45 percent of the municipal water supply was supplied from groundwater source in 1987 (Acres International et al., 2002). Although deep aquifers are tapped for municipal water, individual common households generally use shallow aquifers, because it is easier and cheaper to exploit. In the *Terai*, according to Kansakar (1996), at least 165 MCM of groundwater is extracted annually for domestic purposes from an estimated 800,000 shallow tube wells, and this number is growing every year. But the same shallow aquifers are also being tapped for irrigation use, and the number of shallow irrigation tube wells is also increasing every year, albeit slowly. About 520 MCM is abstracted annually in the *Terai* for irrigation. Although the current level of groundwater abstraction in the *Terai* is small compared to the annual recharge (8,800 MCM), unmanaged growth in irrigation STWs and agricultural development may cause over-extraction (well interference) or pollution in the shallow aquifers. In such situations, the poorest of the poor will be affected the most, because safe and deeper aquifers are out of their reach.

Deep aquifers are generally safe from arsenic, even where the shallow aquifers are found to be contaminated (Bisht et al., 2004). But they are also more expensive to tap. People in arsenic-contaminated groundwater areas are already facing a major problem. No solution has been found that is socially, economically and technologically sustainable. Numerous household level arsenic removal techniques have been developed and tested, but such technologies cannot be the long-term solutions to the arsenic problem, because of low level of awareness, regular maintenance requirements and the recurring cost involved in using these technologies. Locating affordable alternate safe water sources could be the ultimate and long-term solution. The immediate groundwater management need is, therefore, the protection of the known safe aquifers from contamination for future uses and search for safe shallower aquifers in the *Terai.*

Utilization in Irrigation Sector

Irrigation is the other sector where groundwater can find equitable and economic utilization. With a large un-utilized renewable recharge, groundwater in the *Terai* has the potential for playing a central role in poverty reduction and agricultural growth in the country.

Agriculture is the source of livelihood for 86 percent of the population in Nepal. The vast majority of them are small-scale poor farmers. About 31 percent of the population lives below the poverty line. Although the landless population is very small (0.79 percent only), 74.15 percent population has landholding size smaller that 1.0 ha (CBS, 2001/02). Therefore, poverty in Nepal may be attributed mainly to the low agricultural productivity and the unsustainably small landholding sizes (CBS, 2004). Therefore, increasing agricultural productivity could be the key to poverty reduction. Groundwater irrigation can play a central role because it is available in most parts of the *Terai* region. Equitable access to this resource can be achieved through tube well technologies, which can be engineered to suit the farmer's economic capabilities. The main challenge for Nepal is how to improve poor farmers' access to tube well irrigation, without losing control over the groundwater resource exploitation.

Groundwater Management vis-à-vis Tube Well Development in Terai

Policy Environment

Subsidy policy, whether in the form of direct capital cost subsidy or in other indirect forms, plays a vital role not only in groundwater irrigation development but also in resource management. The policy of direct capital cost subsidy and credit facility for the past 20 years, from 1980-2000, was found to actually restrict the growth in STW installations primarily due to the Government's limited capacity to fund. This policy also had a number of undesirable social and economic effects. Studies have shown that the Government's subsidy was consumed mostly by the larger and influential farmers, majority of whom were absentee farmers and were not concerned much about increasing their farm productivity. On the other hand, the small and poor farmers were left out because they could not meet the collateral conditions of the loan program or because they could not afford initial down payment amount or run the tube well profitably due to small land holdings. However, this policy had one advantage; the tube well growth took place in government's full control and the STW growth was well recorded. Such record is highly essential for groundwater management and development planning.

After a policy shift in 2001, the government policy is now to support group-owned shallow tube wells through indirect subsidies like collateral-free group loan and agricultural support programs. But, tube well growth under this program is low, perhaps due to the 'shock effect' from previous years, but also due to the difficulty in forming groups and operating tube wells in groups. As the poor farmers have their lands scattered around, forming a tube well group of 4 ha is quite difficult, and thus this program is proving to be a 'hard nut to bite' for many of the willing small farmers. So, the participants in this program are only a few of the deserving poor and small farmers. According to the government records, only about 2000 STWs have been installed in the *Terai* after this new policy.

Interestingly, however there are no signs in the pump market that the demand has stagnated. The most likely explanation for this is that many farmers are now opting to install tube wells on their own, because the investment on private tube well is attractive enough to offset the 'cost' of having to 'operate in a group'. But, this also means that private STWs outside the government program are growing and will continue to grow faster in the coming years. This is surely going to be a problem for future management because groundwater abstraction data will no more be available.

Socio-economic Environment

The government policies for STW development in Nepal have always tried to address the social issues by technology and economics. A standard STW technology, good for irrigating a minimum of 4 ha plot to become economically viable is being pushed to the farmers, who in majority are small-scale farmers. In the Terai, 74 percent of the households own less than 1.0 ha and 47 percent have less than 0.5 ha of farmland (CBS, 2001/02). For economic viability, the government policy has been to push for group-owned tube wells. But, all small farmers do not have their lands together and moreover, maintaining group cohesion is very difficult. Social conflicts are the main problem in the community STWs, and also in the existing DTWs. It is indicative that 97 percent of the STWs installed during the earlier subsidy policy regime are individually owned, even though a much higher level of subsidy (even up to 85 percent, at one point) was provided for the group tube wells. This trend also is evident in the neighboring South Asian countries, where private STW operators have been the main driving force in bringing the groundwater irrigation development. Hence, utilizing groundwater to lift the numerous small-scale farmers out of poverty is not a straightforward task.

Appropriate Tube Well Technology

For the social conditions mentioned above, and as an alternative to STW, the treadle pump has gained popularity in a short time in Terai. It is a pro-poor and pro-small farmer technology. But, because it requires human labor (Figure 6), this technology places a serious limitation on the farmers' economic growth after a certain point. At present, the only other option available for a successful treadle pump farmer is the standard STW, which is not profitable for his plot size. There is a large section among the *Terai* farmers whose landholdings are between 0.5 ha and 2.0 ha for whom neither a treadle pump nor a standard STW is suitable. Thus, there is a technology gap, which needs to be closed in the benefit of millions of farmers in the *Terai* alone.

Energy for Mechanized Pumping

The electricity distribution network in Nepal serves only 15 percent of the population and 32 percent of the area. Even though the government provides 52 percent subsidy on electricity for irrigation use, very few STW operators have benefited from this policy and almost all STWs are run by diesel. Only 1,050 DTWs are run by electricity only because electrification was built into the project itself, but even those few wells are underutilized because DTW operation is not profitable due to the substantial 'minimum demand charge' on electricity tariff and a relatively much cheaper tariff in neighboring India, which makes their products expensive due to the open door policy between the two nations. Only 29 GWh of electricity was consumed in tube well pumping in the year 2001 (NEA, 2001). This is only 2 percent of the total power consumed (1407 GWh) in that year. The power distribution policy is highly biased towards domestic and industrial consumers, and therefore, STW irrigation does not receive any priority even in the rural electrification programs.

Studies have shown that STW electrification is economically attractive (GDC, 1994), but the initial cost of power connection (Rs. 76,000) is too high for the small farmers to invest. Government has been reluctant to promote STW electrification mainly due to power deficit in the past. Now, with the increased power generation capacity in the country, Nepal has surplus energy, which could be easily supplied to the tube well irrigators. Therefore, a sound national policy is required to utilize and manage both hydroelectricity and groundwater resources, without creating the problems that the neighboring countries are already facing today (see Mehta, this volume).

Water Saving Techniques

Groundwater requires one or another form of energy to be pumped out, and therefore it has a cost. On the other hand, farmers everywhere obtain surface water irrigation more or less free of cost. But ironically, irrigation method and the crops grown are the same whether the source is groundwater or surface water. Naturally, farmers find groundwater irrigation more expensive. However, there are numerous technologies for saving water, for example drip and sprinkler irrigation, but they are seldom used, because those technologies require change in the cropping pattern also. Farmers have been reluctant to bring changes in their irrigation methods and cropping pattern due to inadequate knowledge and limited market. This issue has not received due attention of the planners and the policy makers. Water saving techniques are necessary not only for making groundwater irrigation profitable, but also to minimize stress on the groundwater resource. Success in groundwater management depends on actualizing the slogans of 'more crop per drop' and 'more value from every drop'.

Conclusions

Groundwater development is still in the initial stages in Nepal. There are groundwater resources enough to irrigate nearly one-half of the agricultural land in *Terai*, but they remain largely unutilized. Tube well irrigation can play a central role in poverty alleviation and contribute to improving food security in the country. There are numerous challenges to its development, but even bigger challenges lie in guiding this development towards good groundwater governance. The present approach to groundwater development in Nepal is risky for sustainable groundwater resource management in the long run. Nepal has still time to learn lessons from other countries, especially from the experiences of India, Pakistan, Bangladesh and others, because of similarities in their social, economic and environmental conditions. The groundwater situation in the Kathmandu valley needs to be taken as a 'wake-up call' and should not be ignored.

Different approaches and tools are available for groundwater management, but their effectiveness depends on numerous factors. Solutions that have worked in the post-agrarian industrialized countries may not be suitable for developing countries, where the societies are mainly agrarian in nature. The Government of Nepal is already considering legal mechanisms for groundwater management, but enforcing groundwater regulation is expensive (as in the western countries), or difficult (as in India and China), or even politically impossible (as in India, Pakistan and Bangladesh). Alternatively, various policy measures such as economic incentives, water tariff systems, energy pricing and supply policies, water saving technologies, transparent groundwater monitoring, and so on, may be viable options, and are under discussion in other South Asian countries. But, a deep and thorough understanding of the groundwater socio-ecology is necessary before arriving at workable solutions. A collective effort to bring science into policy discussions by placing alternative approaches to good groundwater governance on the table can only bring this important but vulnerable 'out-of-sight' resource 'into the minds' of the public, the immediate stakeholder, the policy makers and the governments in this region.

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Prospectives and Limits of Groundwater Use in Pakistan

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Abstract

Groundwater use in Pakistan has increased due to increased demand for expanding agricultural, industrial and domestic water use. Due to increasing population and lack of surface water storage, development pressure on groundwater has increased. Annual groundwater abstraction has increased from 10 billion cubic meter (BCM) in the year 1965, to 68 BCM in the year 2002. Unplanned groundwater abstraction has caused excessive lowering of water table in certain areas, mobilization of deeper saline groundwater, secondary salinization and higher pumping costs. More than 80 percent groundwater exploitation is being done by farmers in private sector. About 17 percent area of Punjab and 75 percent area of Sindh province are underlain by saline groundwater. About 70 percent of tube wells in these areas are pumping saline water for irrigation use.

Countrywide soil surface and profile salinity surveys were conducted in 1953-54, 1977-79 and 2001-03. Comparison of data of surface salinity has indicated that salt free land has increased from 56 percent to 73 percent of the approx. 17.0 M ha surveyed. The area affected by surface salinity has decreased from 42 percent to 21 percent. Data of profile salinity within 1.5-meter depth indicated that salt-free profiles have increased from 55 percent to 61 percent and saline profiles decreased from 44 percent to 39 percent. Similarly, severely waterlogged area also decreased in general. This trend is more pronounced in Punjab due to better water management whereas the opposite is true in case of Sindh due to poor water management. There are more than 600,000 irrigation tube wells causing depletion of groundwater (GOP, 2003). Pollution due to agricultural, industrial and human activities, water logging, secondary salinization due to poor drainage, and poor groundwater governance are the main groundwater problems. Use of pesticides has increased from 665 tons in 1980 to 45,680 tons in 1999. Increased use of fertilizers and pesticides has caused groundwater pollution. To overcome these problems, it is recommended to: (i) Develop a groundwater regulatory framework; (ii) Expedite transfer of SCARP tube wells from the public to the private sector; (iii) Strengthen monitoring efforts to determine sustainable groundwater potential and use; (iv) Promote groundwater recharge wherever technically and economically feasible; (v) Delineate areas with falling groundwater table in order to restrict uncontrolled *abstraction; (vi) Improve water management practices; (vii) Capacity building of groundwater centers/ institutes; (viii) Launch awareness/extension campaign for better water management, and (ix) Prepare a database to delineate: (a) groundwater development potential; (b) water quality zones; (c) water table depth zones; and (d) types of tube wells to be installed.*

Introduction

Before the introduction of canal irrigation system, the depth to groundwater in Pakistan was generally 20 to 30 meter below the natural surface level. The sources of recharge were rivers, floods and rainfall. The technology for extraction of groundwater was Persian wheels driven by animals. Hence, the use of groundwater for irrigation was limited. It was practiced mainly near the rivers or in low-lying areas. For centuries, the elevation of the groundwater remained more or less at the same level with only seasonal fluctuations.

After introduction of canal irrigation, in the beginning of the 20th century, the groundwater table started rising till it reached close to ground surface in 1960's. At present, mean annual canal diversions are 128 BCM. A major part of it seeps down from rivers, canals, watercourses and fields and recharges the groundwater. This is an additional and continuous source of recharge to groundwater causing water logging and secondary salinization due to salt accumulation in the top-soil when water from shallow depth evaporates.

Importance of Groundwater

Groundwater is a reliable resource, which can be utilized any time. Groundwater is used for agriculture, drinking water supply and industry all over the world, including Pakistan. Thirty five percent of agricultural water requirements in Pakistan are met from groundwater. Most of the drinking water supplies are also drawn from groundwater.

If cost of one tube well is taken as Rs. 50,000, the total investment for groundwater development in Pakistan will be Rs. 30 billion. Groundwater development is a significant factor in alleviating poverty, especially in rural areas where groundwater access secures the agricultural output. Groundwater usage contributes US$ 1.3 billion to the national economy per year. Studies have shown that due to use of groundwater, yields of crops have increased 150-200 percent and cropping intensities have increased from 70 to 150 percent (Qureshi, 2004).

Groundwater Potential

A simplified Indus Basin water balance is given in Table 1. It is estimated that total annual groundwater recharge is equal to, or less than, discharge which means no further significant groundwater development can be done. In this estimate it is assumed that recharge and discharge from rivers are equal. If evapotranspiration from the groundwater is taken into account the water balance becomes negative.

Groundwater Development

The number of existing private tube wells in Pakistan is over 600,000. The rate of increase is 20,000 tube wells per year. The discharge of the private well-functioning tube wells is 0.8 cusec (23 l/sec).

Groundwater table is falling in almost all the canal commands since 1998. It indicates that current net groundwater abstraction[1] is higher than recharge. Thus the groundwater development at the current pace is unsustainable.

Table 1. Groundwater recharge of the Indus Basin

Location		At head	Infiltration		Recharge to aquifer	
		(BCM)	%	(BCM)	%	(BCM)
1.	Canals Diversions					
	Canals	128	15	19	75	14
	Distributary / Minor	109	8	9	75	7
	Watercourse	100	30	30	60	18
	Fields	70	30	21	90	19
	Crops	49				
	Sub-Total			79		58
2.	Rainfall: Average rainfall of 0.195 m over area of 17.4 M ha.					
	Rainfall recharge	34	50	17	50	8

Challenges of Groundwater Management

Groundwater management is facing the following challenges:

- Depletion due to overdraft;
- Pollution due to agricultural, industrial and human activities (highly polluted cities);
- Water logging and secondary salinization due to poor water management and drainage and unregulated conjunctive use; and
- Poor groundwater governance.

Groundwater Depletion

There is no mechanism for regulating groundwater use in Pakistan. Groundwater rights are not protected under legislation. Anybody having land and sufficient financial resources can install a tube well on his or her land and abstract any amount of water at any given time without consideration of safe yields. Groundwater abstraction from 1965 to 2002 has increased from 10 BCM to 68 BCM. Over 80 percent of groundwater is exploited by the private tube well owners/farmers.

Unplanned pumpage is creating severe management and equity problems. Due to continuous lowering of water table, groundwater is becoming inaccessible

[1]Here, net groundwater abstraction means the groundwater abstracted and not returned to the groundwater, i.e. the water being depleted by evapotranspiration.

to small farmers, which is threatening the sustainability of irrigated agriculture. Already 5 percent of the tube wells in Punjab and 15 percent in Balochistan are beyond the reach of poor farmers. This situation is likely to increase to 15 and 20 percent in the two provinces, respectively (Mohtadullah, 2004).

Deterioration of Groundwater Quality Due to Salinization and Pollution

Groundwater salinity in various provinces is shown in Figure 1. About 17 percent area of Punjab and 75 percent in Sindh is underlain by saline groundwater (TDS>3000 ppm). About 70 percent of tube wells pump saline water for irrigation, which is escalating secondary salinization. Problems are not only due to salinity but also sodicity.

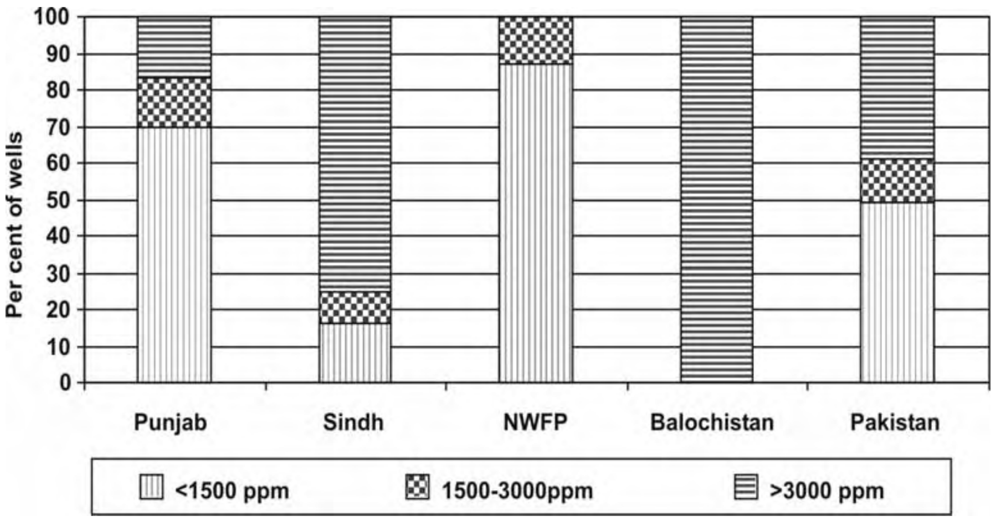

Figure 1. Groundwater quality (TDS, total dissolved solids) in various provinces, measured in existing wells, at depths of 20 to 50m

Leaching from municipal and industrial effluents, fertilizers, pesticides, solid wastes, and disposal of saline drainage effluent and seawater intrusion causes pollution and contamination of groundwater.

Untreated sewage and sullage in urban areas are disposed off into rivers and other surface water bodies through a mixed system of open drains and sewage pipes in the major metropolitan centers and primarily through open drains in the other urban centers. It is estimated that in the province of Punjab, 112 cumecs of municipal and sewerage effluent is being disposed off into the river bodies. The major part, i.e. 83 cumecs, of municipal and sewerage effluent of Lahore city is disposed off into the river Ravi. Leakage of effluents from septic tanks and sewerage drains endanger the aquatic and human life.

A large number of industrial units are scattered throughout Pakistan in rural and urban areas. These units dispose their wastewater into the nearby drainage channels and ponds causing contamination of groundwater and polluting surface water. Some industrial effluents are highly toxic and are discharged without any treatment. It has been estimated that only about 1 percent of the wastewater produced annually in Pakistan is treated before disposal into water bodies (ADB, 2002).

It is estimated that in the province of Punjab, 14 cumecs industrial effluent is being disposed into water bodies. In the Sindh Province, 7 cumecs industrial/ municipal effluent of the Hyderabad region is being disposed into water bodies.

Use of fertilizers and pesticides is increasing day by day for the hunt of higher crop yields to meet the pressing needs of a growing population. For the improvement of crop yields and quality, the government has encouraged the use of insecticides, especially in the production of cotton. As a result, the use of pesticides increased from 665 tons in 1980 to 45,680 tons in 1999 (ADB, 2002). However, excessive application of pesticides has caused the prevailing insect species to develop resistance and has resulted in pollution of surface water and groundwater.

Water Logging and Soil Salinity

Extent of Water Logging

Groundwater table in the Indus Basin canal commands exhibits an annual cycle of rise and fall. It is at its lowest point in the period prior to the monsoon (April/June). Recharged through *Kharif* season (summer) irrigation and rains, it rises to its highest point in October, when it is closest to the land surface before declining again. High watertable conditions after the monsoon, although transitory, interfere with the cultivation of *Rabi* season (winter) crops. The water table position in April/June is, particularly critical and is used as an index of water logging. On average (1993-2002), about 12 percent of the canal command area is severely waterlogged (disaster area), with water table depth less than 150 cm (0-5 ft.).

Overall trend of disaster area for the period from 1978-2003 is depicted in Figures 2 and 3. The disaster area was maximum in 1999 due to heavy rains and abnormal floods in 1998 and minimum in 2000 due to drought conditions in Pakistan.

On an average, the percentage of disaster area slightly decreased from 13.0 percent during 1979-82 to 12.9 percent during 1983-92 and to 11.2 percent during 1993-2003. Data given in Figure 2 and 3 show that the disaster area decreased in Punjab province (due to growth of private tube wells), remained constant in NWFP and increased in Sindh/Balochistan (due to poor water management).

Extent of Soil Salinity/Sodicity

The first countrywide soil salinity survey was conducted in 1953-54 under the Colombo Plan assistance, covering an area of 16.8 M ha. In terms of surface salinity, an area of 9.4 M ha (56 percent of the area surveyed) was salt free, 3.3 M ha (20 percent) was slightly saline, an area of 1.5 M ha (9 percent) was moderately saline and an area of 2.2 M ha (13 percent) was strongly saline whereas, miscellaneous land types included 0.35 M ha (2 percent of the area surveyed). Overall, about 42

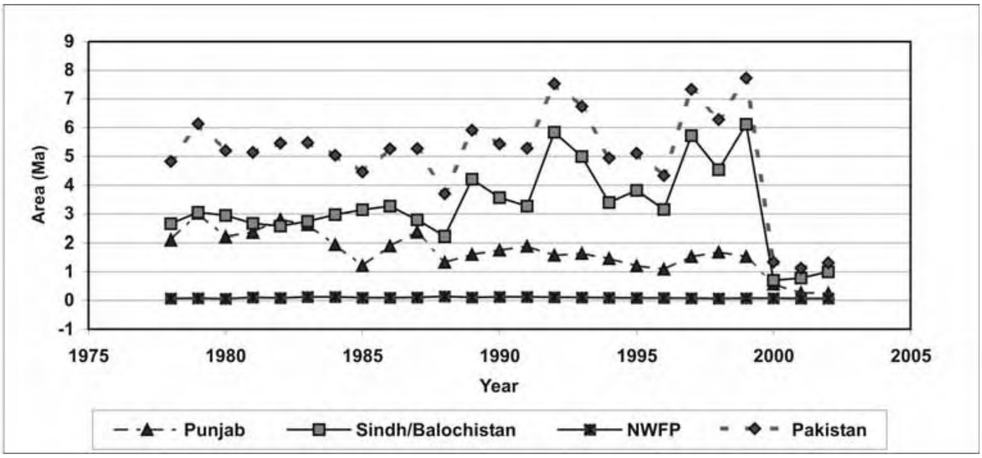

Figure 2. Severely waterlogged (Disaster) area (Groundwater level within 150 cm of the soil surface)

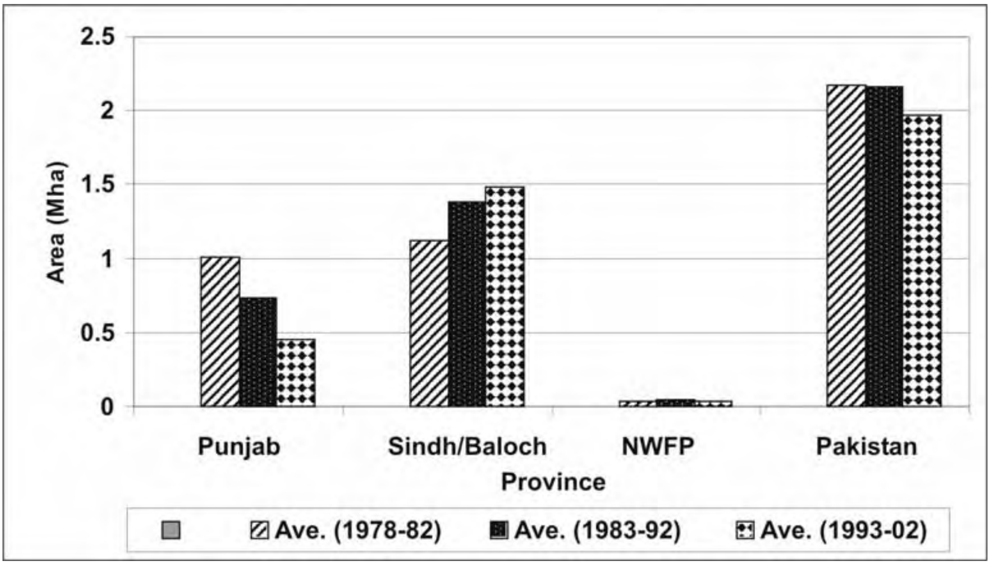

Figure 3. Average severely waterlogged (Disaster) area

percent of the area was affected by surface salinity. Surface salinity of different surveys is depicted in Figure 4 and profile salinity in Figure 5.

The second survey was conducted by WAPDA during 1977-79. In this survey, covering 16.7 M ha, both surface and profile salinity was established through chemical analysis of the soil. In terms of surface salinity, an area of 12.1 M ha (72 percent of area surveyed) was salt-free, 1.9 M ha (11 percent) was slightly saline, an area of 1.0 M ha (6 percent) was moderately saline and 1.3 M ha (8 percent) was strongly saline, whereas miscellaneous land types included 0.43 M ha (3 percent). About 25 percent of the area was affected by surface salinity.

The latest salinity/sodicity survey (2001-2003) has recently been completed by the Soils and Reclamation Directorate (S&R), WAPDA. Under this survey 16.8 M ha area was surveyed. In terms of surface salinity, an area of 12.3 M ha (73 percent of the area surveyed) was salt-free, 1.8 M ha (10 percent) was slightly saline, 0.64 M ha (4 percent) was moderately saline, and an area of 1.1 M ha (7 percent) was strongly saline, whereas miscellaneous land types included 0.94 M ha (6 percent). About 21 percent areas was affected by surface salinity.

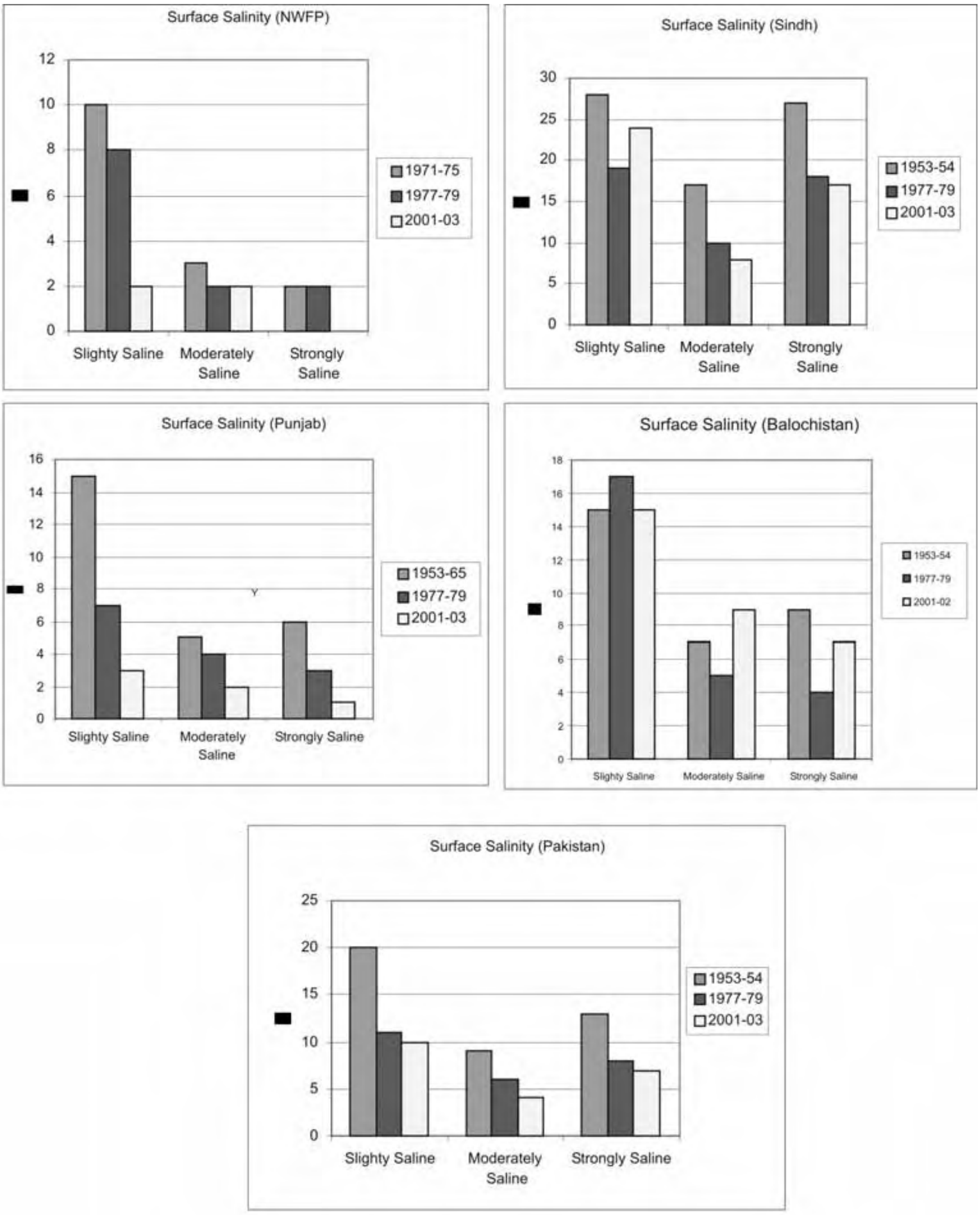

Figure 4. Extent of surface salinity of the Indus Basin during 1953-54, 1977-79, and 2001-03 (in percentage of surveyed area)

Comparison of past surveys indicates that the salt-free lands increased from 56 percent in the early 60's to 72 percent in 1977-79 and 73 percent in 2001-2003. The lands affected by surface salinity have decreased from 42 percent in early 60's to 25 percent in 1977-79 and to 21 percent in 2001-2003.

Profile salinity within 1.5 m depth was surveyed in 1953-65 in Punjab and in 1971-73 in NWFP Province only. The Planning Division, WAPDA in 1977-79, conducted countrywide Profile Salinity Survey. Comparison of profile salinity data shows that profile salinity also decreased in Pakistan as the salt-free profiles increased from 55 percent in 1953-75 to 61 percent in 1977-79 and remained

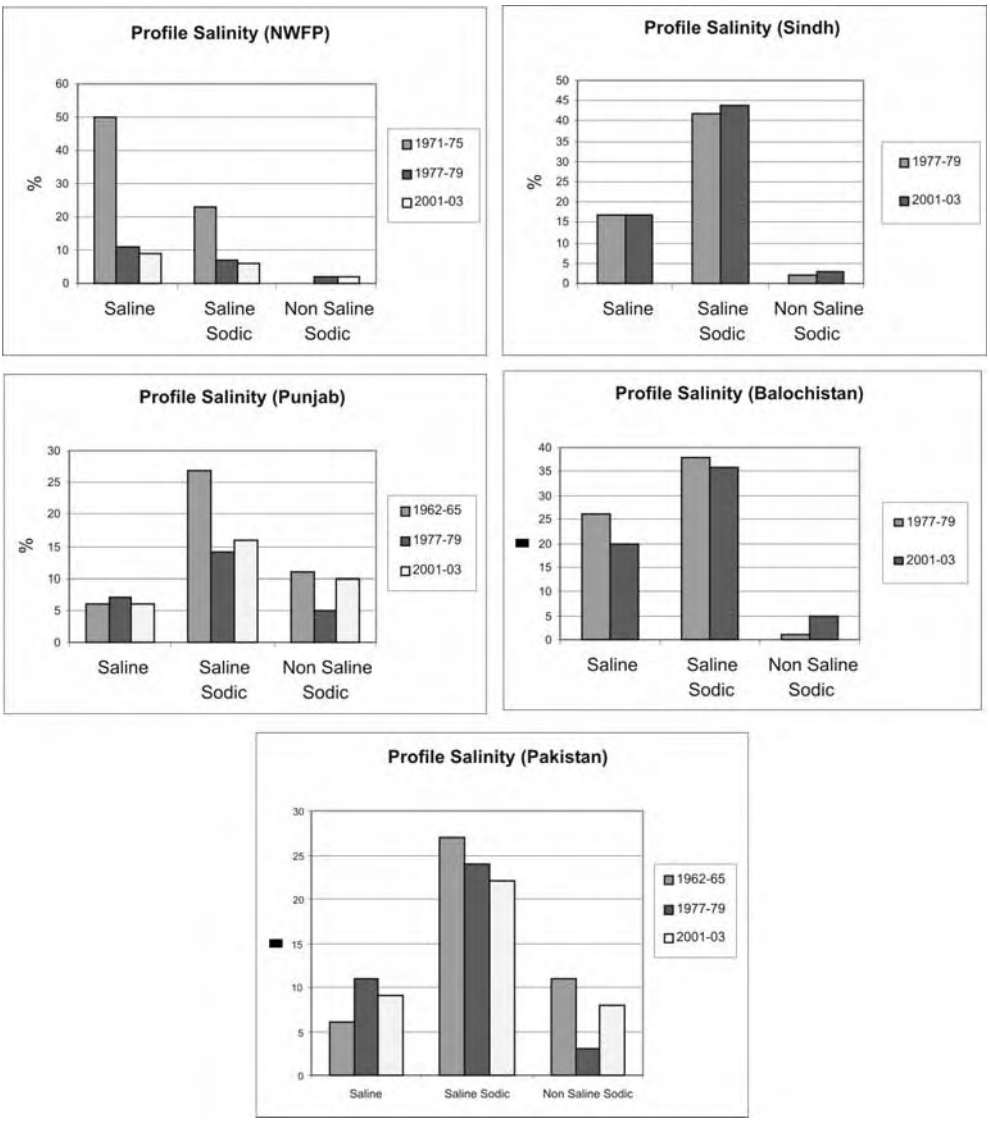

Figure 5. Extent of profile salinity of the Indus Basin during 1977-79 and 2001-03 (in percentage of surveyed area)

unchanged according to latest survey in 2001-03. Saline profiles decreased from 44 percent in 1953-75 to 38 percent in 1977-79 and about 39 percent in 2001-2003.

The reduction in salinity (surface and profile) is primarily due to increased irrigation water supply from surface and groundwater sources, improvement in water management, increased cropping intensity and measures taken by the Government of Pakistan to reclaim the waterlogged and salt-affected lands.

Salinity Control and Reclamation Project (SCARP) Tube Well Management

Initially groundwater exploitation was started in the public sector through SCARP tube wells, which has been taken over by the farmers with their own resources. This has reduced the cost of individual well as well as optimized the pumping according to their requirement. Unfortunately a large number of SCARP tube wells still exist in the public sector, most of which are non-functional. A huge amount is spent every year for O&M of these tube wells from the public sector funds. Urgent measures should be taken to transfer these tube wells to farmers.

Economic and Financial Management

Water is generally not perceived as an economic good and therefore revenue recovery from the users is only a small proportion of the cost, resulting in both a drain on government finances as well as deterioration in service. There is a need, both to recover cost and to raise the standard of the service in the water sector.

Furthermore, the precious water has traditionally been overused and abused. There is a dire need of educating the public of the real value of water to make the users more conscious about it. This would help in reducing demand, would encourage efficiency of usage, and reduce pressure for unnecessary expansion in certain areas.

To address these issues there is need to:

- Promote appropriate water pricing system to ensure recovery of O&M and capital cost;
- Promote the principle of full cost recovery in providing municipal water supply and sewerage services in urban areas to ensure that the responsible operating agencies are financially viable and are able to provide an efficient service;
- Encourage water metering and effective control over wastage of municipal water;
- In the case of industrial effluent disposal, follow the principle of "polluter pays"; and
- Encourage and involve community organizations to prescribe irrigation charges and to become responsible for collection and imposition of penalties for non-payment.

Recommendations

Keeping in view the importance of groundwater, its sustainable use is of utmost importance. Therefore, it is necessary to:

- Develop a groundwater regulatory framework to control and optimize groundwater regulation;
- Expedite transition of SCARP tube wells in the public sector to the private sector, and leave development of fresh groundwater to private sector;
- Strengthen monitoring and groundwater modeling to determine sustainable groundwater potential and prepare groundwater budgets for sub-basins and canal commands and to assess the lateral and vertical movement of saline groundwater interface;
- Promote groundwater recharge wherever technically and economically feasible and also rationalize the surface water supplies;
- Delineate areas with falling groundwater table for restricting uncontrolled abstraction;
- Do not temper with dormant saline aquifer overlain by shallow layer of fresh water;
- Reduce water logging and salinity by improved water management practices;
- Encourage the provinces to prepare a groundwater atlas for each canal command and sub-basin. The atlas should delineate:
  (a) Groundwater development potential
  (b) Water quality zones
  (c) Water table depth zones

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Groundwater Models: How the Science Can Empower the Management?

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Abstract

Protection, restoration and development of groundwater supplies and remediation of contaminated aquifers are the driving issues in groundwater resource management. These issues are further triggered on and driven by the population expansion and increasing demands. To transform the 'vicious circles' of groundwater availabilities into 'virtuous circles' of demands, understanding of the aquifer behavior in response to imposed stresses and/or strains is essentially required. If groundwater management strategies are directed towards balancing the exploitations in demand side with the fortune of supply side, the goals of groundwater management can be achieved when the tools used for solution of the management problems are derived considering mechanisms of supply-distribution-availability of the resource in the system. Groundwater modeling is one of the management tools being used in the hydro-geological sciences for the assessment of the resource potential and prediction of future impact under different stresses/constraints. Construction of a groundwater model follows a set of assumptions describing the system's composition, the transport processes that take place in it, the mechanisms that govern them, and the relevant medium properties. There are numerous computer codes of groundwater models available worldwide dealing variety of problems related to; flow and contaminants transport modeling, rates and location of pumping, artificial recharge, changes in water quality etc. Each model has its own merits and limitations and hence no model is unique to a given groundwater system. Management of a system means making decisions aiming at accomplishing the system's goal without violating specified technical and non-technical constrains imposed on it. A complete groundwater management model is the combination of groundwater simulation models and the optimization methods. A management approach has its own mathematical logic and constraints complemented by the simulation models. It is simulation models, which actually impart groundwater sciences to the management to evaluate potentiality and the fate of the resource for different options and constrained cases. Thus, to meet the increasing demands of water for variety of uses when the supply-side becomes a limiting case or being dragged by the pollution threats, the uses of groundwater models to the management problems are bound to increase and new modeling techniques with inclusion of more real world complexities with improved predictive capacity are bound to dominate the decision process.

Introduction

Groundwater is an important, dependable and major source of drinking water besides agricultural and other uses. It is becoming increasingly important and popular resource, particularly in tropical countries, because of relative ease to access and flexiblility in tapping. It is believed that it can be drawn on demand and also more risk free from pollution than surface sources of water, making it far more attractive to many groups of users. Groundwater moves through aquifers from area of recharge to area of discharge normally at slow rates. These slow flow rates and long residence times, consequent upon large aquifer storage volume, are some distinct features of groundwater systems, which have given rise to its reliability. In South Asia –a region, which has varied problems involving population dynamics and their allied demands and activities, illiteracy, diversity in culture and religions, water use patterns, extremes in rainfall variations, natural disasters and hazards coupled with poor economy; although has one of the world's largest untapped groundwater aquifers–the Ganga-Brahmaputra-Meghna basin–but still holds the problems and challenges to promote sustainable and equitable development of this resource. Development and management of groundwater resources in a sustainable way pose many challenges including threats. Some of the important concerns are: depleting groundwater levels, failure of wells, ever increasing cost of tapping of aquifers, public health problem due to occurrence of carcinogenic elements (e.g., arsenic and fluoride), pollution threat from surface water bodies and leaching, seawater ingress into the freshwater aquifers etc. These added problems beside hydrological and hydro-geological severities including socio-economic forces pose many untoward complexities and challenges in the management of supply-side to meet the requirements in the demand side. Groundwater management is just not making water available for different uses but to evolve a sustainable scheme that would be safe from pollution, ecological imbalances and economic uncertainty besides protecting and restoring the aquifer storage. Irrespective of its economical value, the groundwater resources management has to deal with balancing the exploitation (in terms of quantity, quality, and its interaction with surface water bodies) with increasing demands of water and land uses. These are possible when the hydrological and hydro-geological processes of aquifers for diverse initial and boundary conditions are reasonably understood and integrated appropriately in the chain of development and management objectives.

If the management of groundwater resources is directed towards balancing the supply-side and the demand-side, then for addressing the key issues of the groundwater supply-management, one needs to understand; (i) aquifer systems and their susceptibilities to negative impacts when it is under abstraction stress, and (ii) interaction between surface water and groundwater, such as, abstraction effects and recharge reduction effects. On the groundwater demand-management side, key issues are: (i) social development goals influenced by water use, especially where agricultural irrigation and food production are of primary concern, (ii) regulatory interventions (such as water rights or permits) and economic tools (such as abstraction tariffs, etc.), and (iii) regulatory provisions to ensure government capacity to enforce and user capacity to comply. These complex issues can't be resolved unless their insights are properly understood.

The management of any system means making decisions aimed at achieving the system's goals without violating specified technical and non-technical constraints imposed on it. The hydro-geological processes of the aquifer system govern the technical rules in the groundwater management. Models, which are constructed conceptualizing the physical realism of the hydro-geological processes, are utilized to explore groundwater management alternatives. Prediction, forecasting, and fate evaluation of an aquifer system against some imposed forcing functions involves integration of hydrological and hydro-geological processes with the aquifer properties both on time and space generating huge computational burden, which can not be handled by verbal and simplified approaches. The groundwater modeling is the most preferred alternative. Groundwater modeling is one of the tools of the management that has been used in the hydro-geological sciences for the assessment of the resource potential and prediction of future impact under different circumstances. The predictive capacity of a groundwater model makes it the most useful and powerful tool for planning, design, implementation and management of the groundwater resources.

Prior to advent of the numerical methods and computers, which have tremendously eased the computational scope, groundwater studies were confined, to analytical researches focused mainly towards solving simple boundary problems with limited real life complexities, to field investigations for assessing the aquifer potential, etc. Modeling of aquifer responses and multi-allocations management problem of groundwater resources was a rarity. Intensive field investigations and data acquisition together with advanced instrumentations have facilitated further understanding of the physical processes of groundwater storage and movement including science of heterogeneous aquifer systems. Needless to mention that this has encouraged development of generalized computer codes. Socio-economic and socio-cultural development besides food security and increasing environmental concerns driven by the population growth, are other factors, which are multiplying the complexities of management and development of the groundwater resources. Neither the availability of groundwater resources is plenty (but limited) nor there are much scope left to increase the overall quantity. Replenishable quantity forms the main guiding factor to the availability side, while the demand-side factors are rising both on number and magnitude. The multi-dimensional demands side by side the increasing environmental concerns along with the limitations of availability call for development of advanced to most advanced approaches of management satisfying the conditions of technicalities.

The paper presents a state-of-art of groundwater modeling along with an overview of groundwater flow and contaminant transport modeling including their roles in management of groundwater resources. It is also intended to focus some key issues of supply and management of groundwater resources, which are real concern in the planning and policy decisions, and may pose challenge to the researchers in future years. The scope of the paper is restricted to the groundwater system in porous media.

Groundwater System

A groundwater system comprises of the surface water, the geological media containing the water (such as, aquifer), flow boundaries and sources (such as, recharge), and sinks (such as, withdrawals). Aquifers are rocks or sediment that act as storage reservoirs for groundwater and typically characterized by high porosity and permeability. An aquiclude is rock or sediment that represents a barrier to groundwater flow. Infiltrated water into open aquifers from top represents recharge. Pumping, evapo-transpiration and loss through boundaries represent withdrawal. Open aquifers contain a saturated zone where pore spaces are filled with water. The water table is the top of the saturated zone. Water enters closed (artesian) aquifers from a recharge area..

Let us consider a control volume of a lumped groundwater system as shown in Fig.1. At a given period of time, let all the components of sources and sinks (Fig.1) be in position. If the system truly represents the water balance over a period of time (say, Δt), then the difference of inflow to the system and outflow from the system should equal to the accumulated storage in the system over that time. This accumulated storage of groundwater would be available in the control volume at the end of the time period, Δt. If the process continues for a finite time, t (= n Δt, where n = an integer), the accumulated storage at the end of time, nΔt, would be the resulting effect of inflows and outflows in the control volume, and the water level corresponding to this resulting effect would give shape to the groundwater level. If the control volume represents a groundwater basin, and the time period size is taken relatively large, then the computed accumulated storage of recharge months (monsoon period) gives the lumped assessment of the groundwater availability in that basin. In regular coordinate systems and for control volume of regular size with infinitely small dimension, if the processes are linked to the aquifer properties and mechanism then, what one obtains, is the groundwater flow equation. The groundwater balance equation for the control volume as shown in Fig. 1 for a time period, Δt, can be written as:

$$\left(R_i + R_c + R_{ir} + R_t + R_{is} + I_b\right)\Delta t = \left(E_t + G_w + R_{es} + O_b\right)\Delta t + \Delta S \tag{1}$$

All the components of equation (1) can be estimated using independent methods, or, one of the unknown components can be estimated if all other components are known.

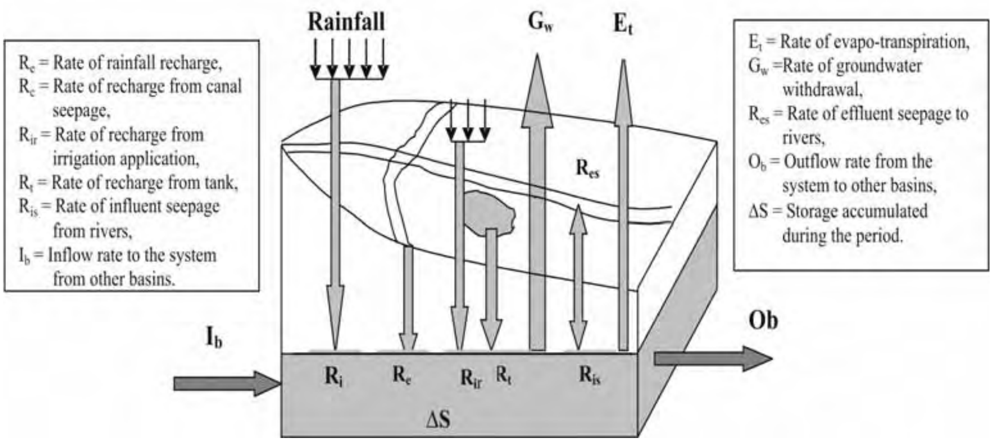

Figure 1. Schematic of a control volume of lumped groundwater system

Groundwater Models

In general, models are conceptual descriptions or approximations of physical systems or processes, which are translated into well-posed mathematical equations. The mathematical representation converts the physical system into the conceptual framework of computation through mathematical variables that helps in performing the job of simulation and scenarios development for the imposed stresses and/or strains without physically intervening into the system. Model is, thus, quantitative representation of the relationships among the entities or processes in a system. Models are used to bring quantitative data and qualitative information together in a predictive framework. A groundwater model may be defined as a simplified version of a groundwater system that approximately simulates the relevant excitation-response relations of the system. Since real-world systems are very complex, there is a need for simplification in policy planning and management decisions. The simplification is introduced as a set of assumptions, which expresses the nature of the system, their features and behaviors that are relevant to the problem under investigation. These assumptions together with other factors would relate to the geometry of the investigated domain, the various heterogeneities, the nature of the porous medium, the properties of the fluid involved, and the type of flow regime under investigation etc. Being a simplified version of real-world system, and hence no model is unique to a given system. Different sets of simplifying assumptions result in different models. However, a model is generally constructed for a particular aquifer by specifying the area to be analyzed, conditions at the boundaries of the area, and parameter values within the aquifer, and they are constructed by mathematical equations, which describe the physical laws that groundwater must obey. The usefulness and accuracy of computing the values of a model depends on how closely the mathematical equations approximate the physical system being modeled and what competence level of understanding one has about the physical system and the assumptions embedded in the derivation of the mathematical model.

The major processes associated with groundwater problems are fluid flow, solute transport, heat transport and deformation. Accordingly, different models associated with these processes are used for different purposes. Groundwater flow models are used for the management of groundwater resources. Solute transport models are used for the study of groundwater quality problems including seawater intrusion. Heat transport models are used to study geothermal problems. Deformation models are used to study the subsidence of groundwater as a result of excessive pumping. However, when we talk about groundwater resource management, we often refer the groundwater flow and solute transport models. A groundwater model can have two distinct components: (i) groundwater flow component, and (ii) groundwater contaminant transport and reactive reactions component. Groundwater flow and contaminant transport modeling together play an important role in the characterization of groundwater bodies and the management of groundwater. A groundwater flow modeling is pre-requisite for developing a contaminant transport model of an area of interest. A groundwater flow model can provide a quantitative assessment of groundwater resources along with the following components: (i) estimating groundwater recharge, discharge, and storage at spatial scale; (ii) assessing the cumulative effects on existing and proposed water resources uses and developments; and (iii) evaluating the cumulative impact on water resources of various water management options. A groundwater contaminant transport model, however, assists in predicting the transportation or movement of dissolved constituents including their chemical reactions in groundwater and soil matrices.

Elements of Groundwater Model Development

Elements of a groundwater model can be divided into two distinct processes: (i) model development, and (ii) model application (Fig. 2). The model development deals with process description and mathematical formulations of the processes, and bringing them into the computational mode by developing computer code, i.e., software part. The model application is the use of the computer code for a specific purpose. Fig.2 illustrates elements of a groundwater model development. A groundwater model development process requires understanding and skill of two broad components: (a) conceptualization, and (b) mathematical formulations. The contents of conceptualization deal with set of assumptions that verbally describe the system's composition, the transport processes that take place in it, the mechanisms that govern them, and the relevant medium properties. The conceptualization is one of the most important steps in the modeling process. Oversimplification may lead to a model that lacks the required information, while under-simplification may result in a costly model, or in the lack of data required for model calibration and model parameter estimation or both. The step next to the conceptual representation is the mathematical modeling. The complete statement

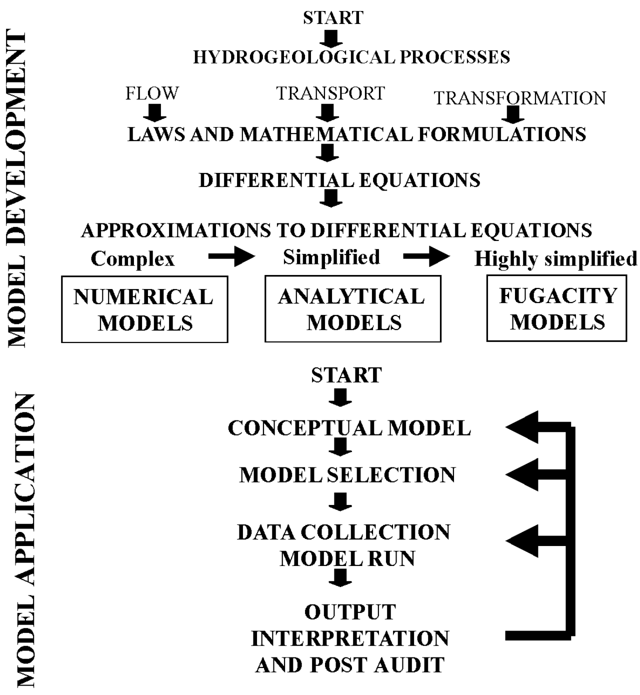

Figure 2. Development process of a groundwater model

of a mathematical model consists of: (i) a definition of the geometry and its boundaries, (ii) an equation (or equations) expressing the water balance, (iii) flux equations that relate the fluxes, (iv) constitutive equations that define the behavior of the fluids and solids involved, (v) an equation (or equations) that expresses initial conditions, (vi) an equation (or equations) that defines boundary conditions describing interaction with its surrounding environment. The solution to the mathematical equations yield the required predictions of the real-world system's behavior in response to various sources and/or sinks. The mathematical model contains the same information as the conceptual one, but expressed as a set of equations which are amenable to analytical and numerical solutions. All the mathematical equations are expressed in terms of the dependent variables, and the number of equations included in the model must be equal to the number of dependent variables.

Groundwater Modeling

Modeling is not just about entering data into existing modeling packages and reporting results. Development of the groundwater model for a real world and its application requires thorough understanding of the groundwater system for refinement of the conceptualized elements to maximize knowledge about current state of groundwater body and the possible future impacts of proposed development. Groundwater models are used as tool for the assessment of the resource potential and prediction of future impact under different circumstances/stresses. Predictive capacity of a model makes it the most useful tool for planning, design, implementation and management of the groundwater resources. Groundwater modeling provides the framework to decide and predict the fate of decision variables of the hydro-geological processes in response to the stresses and/or sinks acting on the system.

The very first step in the modeling process is the construction of a conceptual model. Selecting the appropriate conceptual model for a given problem is one of the most important steps in the modeling process. The selection of an appropriate conceptual model and its degree of simplification depends on:

- Objective of the management problem,
- Available resources
- Available field data
- Users and beneficiaries attitude to the use of water,
- Legal and regulatory framework applicable to the situations.

The next step in the modeling process is to express or to bring the conceptual model in the form of a computational framework. Existing software packages or mathematical equations can be used as computation tools. Fig. 3 illustrates a simple diagram of a model application process (Bear *et al.*, 1992).

A successful model application requires appropriate site characterization and expert insight into the modeling process. No model can be used for predicting the behavior of a system unless the numerical values of its parameters have been determined by some identification procedure. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties

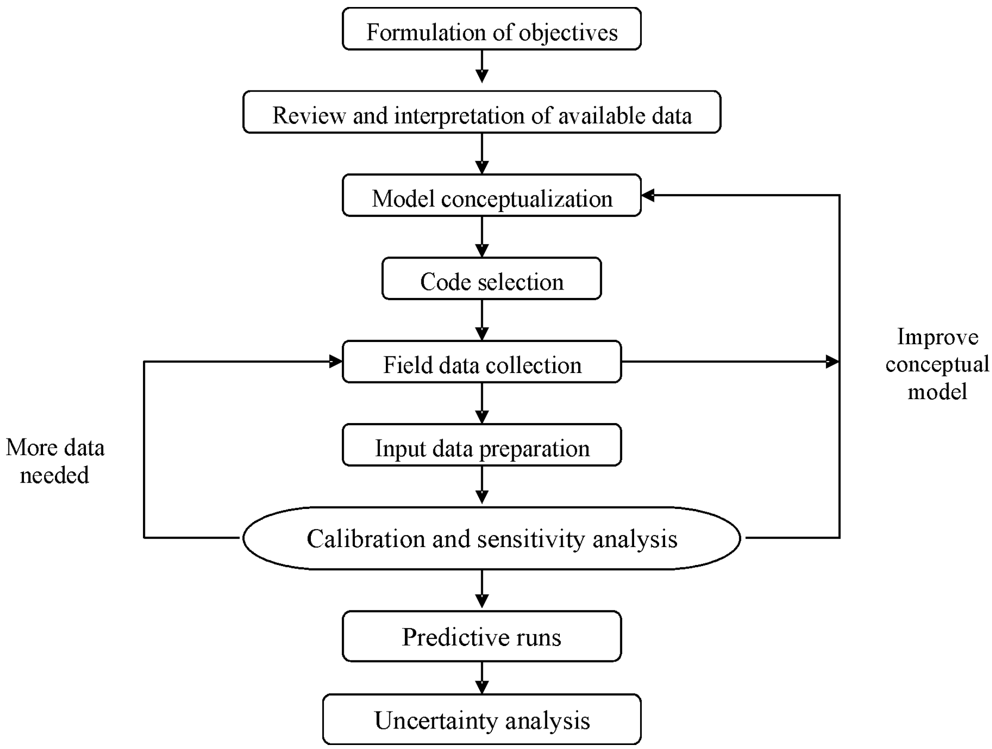

Figure 3. Model application process *(Source: Bear et al., 1992)*

in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions.

Modeling Equations

Groundwater flow and solute transport are governed by the principles of conservation of momentum and mass. Mathematically, these conservation principles, together with empirical laws can be expressed as a set of partial differential equations. Subject to initial and boundary conditions as well as appropriate source functions, the equations can be solved analytically or numerically to interpret observations or predict certain phenomena.

The modeling equations basically originate from water balance or mass balance of flow and contaminant transport in porous medium domains. A number of simplifying assumptions are usually made before any of these equations are written. The well-known Darcy's law can be derived from simplified assumptions of momentum balance equation.

Groundwater Flow Equation

The generalized groundwater flow equation for a 3-Dimensional saturated flow in porous medium is written as (Bear, 1972; Bear, 1979):

$$S_o \frac{\partial \phi}{\partial t} = \nabla * \{K * \nabla \phi\} + Q \tag{2}$$

where S_o is the specific storativity of porous medium, ϕ is the piezometric head, *K* is the hydraulic conductivity tensor, Q is the volumetric flux per unit volume representing source/sink term, and ∇ is the vector operation in the xyz plane.

The specific storativity, S_o, is defined as the volume of water added to storage in a unit volume of porous medium, per unit rise of piezometer head. Hence, left hand side of equation (2) expresses the volume of water added to storage in the porous medium domain, per unit volume of porous medium per unit time. The divergence of flux vector, q *(= - K *Ñf)* expresses the excess of outflow over the inflow per unit area, per unit time. In equation (2), the operators are in the three dimensional space. The variable to be solved is *f (x,y,z, t).* Thus, equation (2) states that the excess of inflow over outflow of water in a unit volume of porous medium, per unit time, at a point, is equal to the rate at which water volume is stored.

The generalized groundwater flow equation for a 2-dimensional saturated flow in confined aquifer is written as (Bear, 1972; Bear, 1979):

$$S \frac{\partial \phi}{\partial t} = \nabla * \{T * \nabla \phi\} - P(x,y,t) + R(x,y,t) \tag{3}$$

where *S* is the aquifer storativity, ϕ is the piezometric head, *T* is the aquifer transmissivity tensor, *Ñ* is the vector operation in the xy plane, *P(x,y,t)* is the rate of pumping (per unit area of aquifer), and *R(x,y,t)* is the rate of recharge (per unit area of aquifer).

The storativity, *S*, is defined as the volume of water added to storage in a unit area of aquifer, per unit rise of piezometer head. Hence, left hand side of equation (3) expresses the volume of water added to storage in the aquifer, per unit volume of porous medium per unit time. The divergence of flux vector, q *(= - T *Ñf)* expresses the excess of outflow over the inflow per unit area,per unit time. In equation (3), the operators are in the two dimensional horizontal coordinates, and the variable to be solved is *f (x,y, t).* Thus, equation (3) states that the excess of inflow over outflow of water in a unit area of an aquifer, per unit time, at a point, is equal to the rate at which water volume is stored.

The governing equation for 3-dimensional density–dependent miscible flow uses for a coastal aquifer may be written as (Guo and Langevin, 2002):

$$\frac{\partial(\rho\ n)}{\partial t} = \bar{\rho}\, Q - \nabla * (\rho\ q) \tag{4}$$

in which ρ is the variable fluid density; ‘ρ is the density of water entering from a source or leaving through a sink; n is the porosity; Q is the volumetric flow per unit volume of aquifer representing sources/sinks; q is the specific discharge vector, with its component given by:

$$q_x = \frac{K_x}{\mu}\frac{\partial \phi}{\partial x} \qquad q_y = \frac{K_y}{\mu}\frac{\partial \phi}{\partial y} \qquad q_z = \frac{K_z}{\mu}\left[\frac{\partial \phi}{\partial z} + \rho\ g\right] \tag{5}$$

μ being the dynamic viscosity; g being the acceleration due to gravity; K being the hydraulic conductivity tensor.

Contaminant Transport Equation

The generalized contaminant transport equation for a 3-dimensional saturated flow in porous medium is written as (Bear, 1972; Bear and Bachmat, 1984; Bear and Verrrujit, 1987):

$$\frac{\partial\{nC\}}{\partial t} = -\nabla * \left\{Cq + nJ^* + nJ\right\} + R_c + \sum_{k=1}^{N} R_k \tag{6}$$

where C is the concentration of considered contaminant, n is the porosity of porous medium, q is the specific discharge of water (= volume of water passing through a unit area of porous medium per unit time), J^* is the diffusive flux of contaminant per unit area of fluid in micro-scale, J is the diffusive flux of contaminant per unit area of fluid in macro-scale, R_c is strength of contaminant source (added quantity per unit volume of porous medium per unit time), and R_k is the chemical reaction term.

The transport equation is linked to the flow equation, as:

$$q = -K * \nabla\phi \tag{7}$$

The left hand side of equation (6) expresses the mass of the contaminant added to storage per unit volume of porous medium per unit time, while the first term on the right hand side of equation (6) expresses the excess of the contaminant's inflow over outflow, per unit volume of porous medium, per unit time. The second and third terms on the right side of equation (6) express respectively the added mass of various sources and the chemical reaction component. The total flux is made up of an advective flux with fluid, a diffusive flux, and a dispersive flux. The diffusive and dispersive fluxex appearing in equation (6) are expressed in terms of the concentration, C, as:

$$J^* = -D_m * \nabla C \quad ; \qquad J = -D * \nabla C \tag{8}$$

where D_m is the coefficient of molecular diffusion in a porous medium, and D is the coefficient of dispersion.

The governing equation for 3-dimensional variable density transport equation can be expressed in the same way as equation (6) but the density can be written by an empirical equation as a function of concentration suggested by Baxter and Wallace (1916):

$$\rho = \rho_f + EC \tag{9}$$

in which, E is a dimensionless constant, approximately value of 0.7143 for salt concentrations ranging from zero for freshwater to 35 kg/m^3 for seawater and ρ_f is the fluid density of freshwater.

Model Coefficients and their Estimation

In describing movement from microscopic level to macroscopic level, various coefficients of transport and storage are introduced. The permeability of porous medium, aquifer transmissivity, aquifer storativity, and porous medium dispersivity are examples of model coefficients. Permeability and dispersivity are examples of coefficients that express the macroscopic effects of microscopic configuration of the solid-fluid interfaces of a porous medium. The coefficients of aquifer storativity and transmissivity are introduced by the further averaging of the three-dimensional macroscopic model over the thickness of an aquifer in order to obtain a two-dimensional model. All these coefficients are coefficients of the models, and their interpretation and actual values may differ from one model to the next. The activity of identifying these model coefficients is often referred to as the identification problem.

The values of the coefficients for a considered model are obtained by investigating the available data of real-world aquifer system on: (i) initial conditions of the system; (ii) excitations of the system, as in the form of pumping and artificial recharge and changes in boundary conditions; and (iii) observations of the response of the system, as in the form of temporal and spatial distributions of water levels and solute concentrations. Various techniques exist for determining the "best" or "optimal" values of the coefficients. Some techniques use the basic trial-and-error method, while others employ more sophisticated optimization methods. In some methods, a priori estimates of the coefficients, as well as information about lower and upper bounds, are introduced. Beside these, another unique method, called inverse problem, is also used to determine the model coefficients.

Methods of Solution

Once a well-posed model for a given problem has been constructed, including the numerical values of all the model coefficients, it must be solved for any given set of excitations (i.e., initial and boundary conditions, sources and sinks). The preferable method of solution is the analytical one, however, for most cases of practical interest, this method of solution is not possible due to the irregularity of the domain's shape, the heterogeneity of the domain with respect to various coefficients, and various non-linearities. Instead, numerical models are employed.

As a numerical model is derived from the mathematical equations and interpretations, it need not necessarily be considered as the numerical method, but as a model of the problem in its own right. With the introduction of computers and their application in the solution of numerical models, solutions of complex groundwater problems have become relatively easy.

Analytical Models

Such models enable investigators to conduct a rapid preliminary analysis of groundwater contamination and to perform sensitivity analysis. A number of simplifying assumptions regarding groundwater system are necessary to obtain an analytical solution. For application and analyzing an analytical model in context to the "real-life" problem, it requires sound professional judgment and experience. Analytical models should be viewed as a useful complement to numerical models.

Numerical Models

Depending on the numerical technique(s) employed in solving the mathematical model, there exist several types of numerical models:

- Finite-difference models
- Finite-element models
- Boundary-element models
- Particle tracking models
  - Method of characteristics models
  - Random walk models, and
- Integrated finite difference models.

The main features of the various numerical models are:

- The solution is sought for the numerical values of state variables only at specified points in the space and time domains.
- The partial differential equations replaced by a set of algebraic equations written in terms of discrete values of the state variables at the discrete points in space and time.
- The solution is obtained for a specified set of numerical values of the various model coefficients.
- Because of the large number of equations, which are to be solved simultaneously, a computer program is prepared.

In the present global computational environment, software codes of almost for all classes of problems encountered in the management of groundwater are available. Some codes are very comprehensive, popular and widely used, such as; MODFLOW & MT3D (Modular Three-Dimensional Finite-Difference Groundwater Flow Model) developed by U.S. Geological Survey (McDonald and Harbaugh, 1988) and associated modules; MODPATH, RT3D; GMS (Groundwater Modeling Environment for MODFLOW, MODPATH, MT3D, RT3D, FEMWATER, SEAM3D, SEEP2D, PEST, UTCHEM, and UCODE); FEFLOW (Finite Element Sub-surface Flow System); Groundwater Vistas (Model Design and Analysis for MODFLOW, MODPATH, MT3D, RT3D, PEST, and UCODE); HST3D (3-Dimensional Heat and Solute Transport Model); SEWAT(Density Driven flow and transport model); SUTRA (2-Dimensional Saturated/ Unsaturated Transport Model) etc. The strength and computational competency of these models are well recognized amongst the groundwater modelers.

Groundwater Resource Management Model

Management of groundwater resources primarily involves the allocation of groundwater supplies in terms of quantity and quality to competing demands. Groundwater models are utilized to explore groundwater management alternatives. A groundwater management model is the combination of groundwater simulation models and the optimization methods, which are coupled together to produce a single program to optimize management objectives while meeting physical and technical constraints on groundwater behavior. The optimization scheme is the mathematical transformation of management objectives (e.g., maximize benefits or effectiveness, or, minimize cost) or design criteria and the physical constraints. In a groundwater system, management decisions may be related to rates and location of pumping and artificial recharge, changes in water quality, location and pumping in pump-and treat operations, etc. The resulting optimization problem is then solved to determine the optimal strategy for dealing with the management objectives and design criteria. However, the value of management's objective function usually depends on both the variables and on the response of the aquifer system. Constrains are expressed in terms of future values of state variables of the considered groundwater system. An essential part of a good decision-making process is that the response of a system to the implementation of contemplated decisions must be known before they are implemented.

Optimization modeling involves the development of a systematic method of determining optimum water supply strategies that would satisfy various environmental and hydrologic requirements. The purpose of this type of water supply strategy is to balance the projected needs against available sources. Although the simulation models provide the resource planner with important tools for managing the groundwater system, the prediction tools don't identify the optimal groundwater development, design and operation policies for an aquifer system. In contrast, groundwater optimization models identify the optimal planning or design alternatives in the context of the system objectives and constraints. It is the groundwater planners or the decision makers, who has to decide the best among the possible alternatives. Fig.4 represents a generalized structure of a simple Simulation-Optimization framework. Structurally, the coupled Simulation-Optimization (S/O) models have an optimizer linked to an external simulator. The S/O approach is appealing because it can readily use existing simulation models and can account for the nonlinear and complex behavior of a groundwater flow system.

Both linear and non-linear optimization techniques are used to develop groundwater management models. Simplex method for linear problems, sequential linear programming for nonlinear problems, and branch and bound algorithm for mixed integer problems are some conventional techniques of optimization. Besides those, the other advanced techniques developed in recent time for optimization of groundwater quantity and quality management strategies, and also for remediation are: (i) nonlinear chance-constrained groundwater management model (Tung, 1986; Wagner and Gorelik, 1987; Gailey and Gorelik, 1993; Tiedman and Gorelik, 1993), (ii) simulated annealing method (Dougherty and Marryott, 1991), (iii) Sharp interface model for seawater intrusion (Finney et al., 1992), (iv) simulation-optimization model for well field, capture zone design, groundwater levels predictions for pumping policy, supply-demand scheduling, etc (Varlein and Shafer, 1993; Chau, 1992; Danskil and Freckleton, 1992; Lall and Lin, 1993; Gharbi and Peralta, 1994). The method of optimization is another subject, which requires a separate discussion and is not included in the scope of the paper.

Need of Groundwater Management Models

Management problems of groundwater resources primarily deal with three aspects: (i) supply-side components (availability and distribution), (ii) demand-side components (allocations for different requirements), and (iii) impinging components

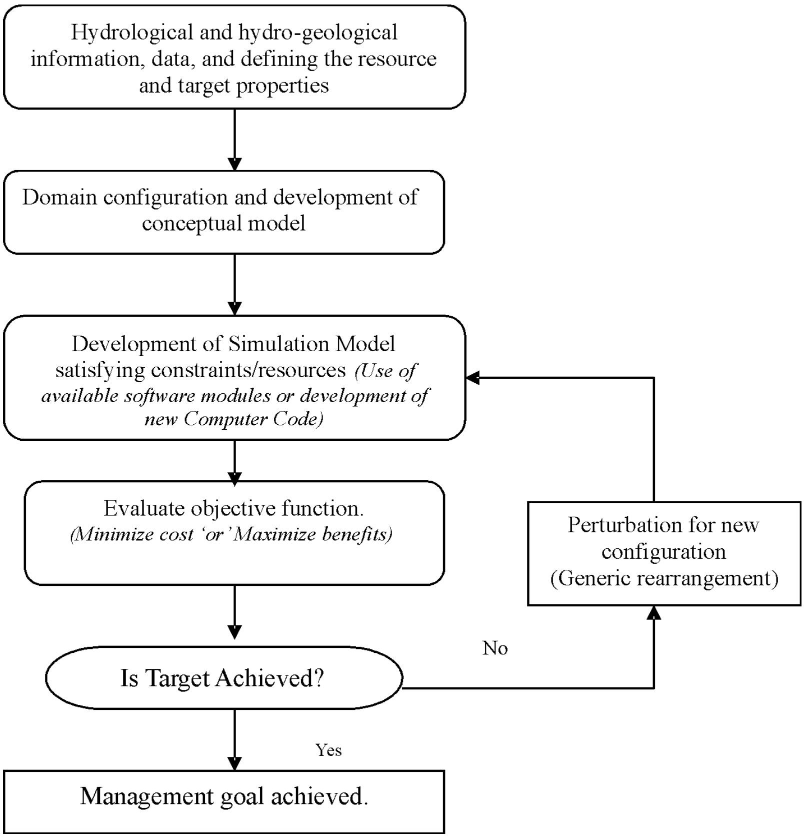

Figure 4. A generalized structure of a simple simulation-optimization framework

(threat to the availability). The supply-side and demand-side components mostly deal with quantitative aspect, while the impinging issues could be of both quantitative and qualitative form of the groundwater system. Impinging or encroaching issues mainly indulge into the prospect of availability and demand as well. To exemplify the components of exploitations and their consequences with the components of availability, let us look into the schematized Fig.5; in which some of the key issues of supply, demand and impinge components are depicted, which are self explanatory. The supply-side components are those, which create positive potential to the storage (i.e., increases the storage volume), the demand-side components are those, which withdraw water from storage (or, reduce the storage potential), while the impinging components have the characteristics of defunct and reduce of the potential of storage. Causes and factors responsible to these issues are also illustrated in the figure. To the supply-side, recharge from rainfall and irrigation application, and seepage from surface interactions are the main components of supply of water to the groundwater system, while all other factors (such as, permeability, hydrogeology, aquifer properties, etc) give shape to the availability and distribution of flow in space and time. The rainfall recharge and the seepage from surface waters depend largely on the rainfall, whose distributions also vary on space and time, but by and large, the fluctuation of

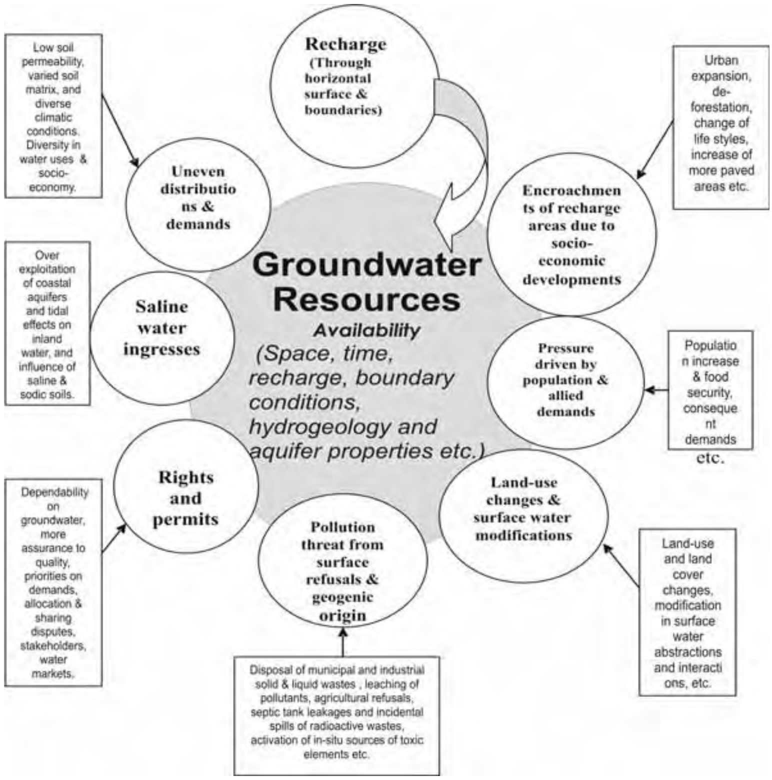

Figure 5. Supply-Demand-Encroachment components of an exploited groundwater resource system

average annual rainfall between years at a specific location is very less except severe years. Thus, recharge area remaining same; the supply of replenishable groundwater resources in an area does not change much over the years but turns into a limiting state.

The demand-side constitutes all those components, which are driven mainly by the population expansion and associated demands, food security, socio-economic development and regulatory provisions, etc. Unlike the characteristics of supply-side components, the characteristics of demand-side components vary in magnitude between years besides spatial variation. It is the multidimensional demands including their increase over time, which brings susceptibility to the supply-side. Multiple demands supported by limited supply eventually suggest for requirement of management decisions for operation of the system.

Impinge on the availability resulting from the exploitations of the demand-side appends threat in terms of quality and quantity both on time and space to the existing storage and to the future storage. These unfavorable factors originate from pollution due to solid and liquid waste disposal, refusal of agricultural waste, septic tank leakages, change of oxidation-reduction potential in hydro-geological environment due to overexploitation of groundwater, seawater intrusion, influence of saline and sodic soils to the groundwater, etc., while others, such as, encroach to the recharge zones, land-use changes, etc, are due to the socio-economic and socio-cultural development of the society. Economic development side by side increasing health awareness are giving rise to problems of right to use of groundwater, and permit to stakeholders for use of groundwater. Conflict in sharing of groundwater of a common pool is another emerging problem. Management of coastal aquifers against threat of saline water ingress requires special skill and attention. Groundwater contamination and its mobilization and spreading in the soil pores and in the groundwater are emerging as gigantic issues other than the groundwater flow management. Vulnerability of contamination to the freshwater zones of a contaminated aquifer would increase if the contaminated aquifers remain untreated. Aquifer restoration and remediation are, therefore, needed to ensure the risk free replenished groundwater. The management decisions cannot be prejudiced to quantity without assuring the quality of water being supplied. These multi-faceted complexities insist upon to develop appropriate decision support system for management of groundwater system.

The purpose of the groundwater resource management model being determining the optimal allocation strategy against demands under the constrains of availability and supply or with some limiting conditions either to the supply-side or to the demand-side, it is essentially required to recognize and understand the characteristics and behavior of associated components. The characteristics and behavior of components of a system can be described when their physical realism are understood to the possible extent. More is the understanding of the hydrological and hydro-geological processes better is the prospect of conceptualize framework of the models. Figure 6 depicts some of the key issues and factors, which are to be addressed for achieving the goal of groundwater resource management.

Finally, a management approach is said to be perfect, if the demand-side elements balance with its supply-side inputs. In case of groundwater management, the elements are: (i) hydrogeologic and socio-economic conditions of the system, (ii) regulatory interventions, (iii) regulatory provisions, and (iv)costs and benefits of management activities and interventions. Figs.7 and 8 depicts how a supply

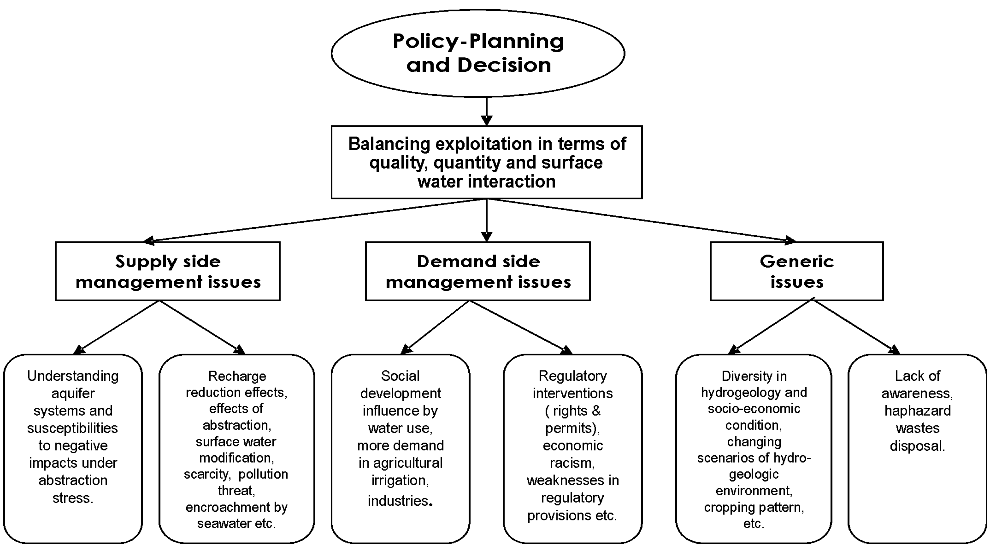

Figure 6. Key issues of policy planning and decisions of groundwater resource management

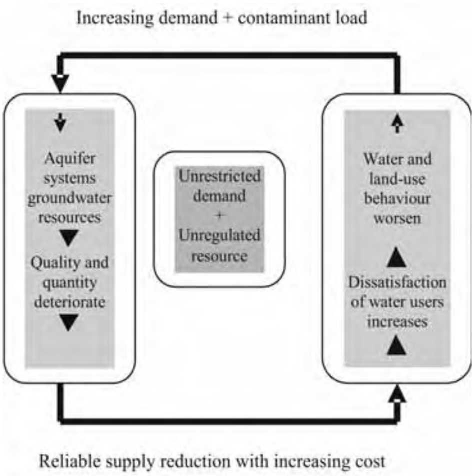

Figure 7. Supply-driven groundwater development – leading to a vicious circle *(Source: GW-MATE, 2004)*

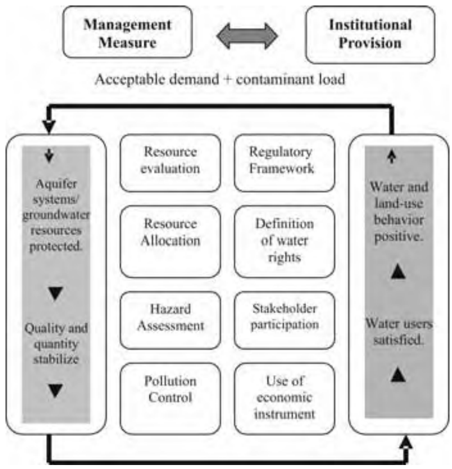

Figure 8. Integrated groundwater resource management – leading to a virtuous circle *(Source : GW-MATE, 2004)*

driven 'vicious circle' of groundwater development can be transformed into a 'virtuous circle' of integrated groundwater resource management through integration of supply-side management with the demand-side management.

Concluding Remarks

Models are conceptual framework of physical systems represented by well-posed mathematical equations derived from the physical laws that the system must obey. Models are used to bring quantitative data and qualitative information together in a predictive framework, and hence can be regarded as tools in insight the behavior of a system in response to imposed stresses/strains without intervening physically into the system.

Groundwater models are simplified versions of a conceptualized groundwater system that approximately simulates the relevant excitation-response relations of the system. Being a simplified version of real-world system, no model is unique to a given system. Groundwater models are one of the management tools used for the assessment of the resource potential and prediction of future impact under different circumstances. Predictive capacity of a model makes it the most useful tool for planning, design, implementation and management of the groundwater resources.

Groundwater management model is a coupled framework of the groundwater simulation models and the optimization methods that produces a single program to optimize management objectives while meeting physical and technical constraints on groundwater behavior. It is simulation models, which actually impart science of hydrological and hydro-geological processes into the management approaches. Optimization method has its own mathematical authenticity. These facts bring strength to the genuineness of a groundwater management model.

Increasing pace of multidimensional demands pulled by the limiting state of supply and pollution threats direct only towards development and use of best management approach.

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Watershed Management and Water Harvesting as Strategic Tools for Groundwater Augmentation

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Abstract

The conservation, development and management of water are pivotal to the concept of 'watershed management'. Watershed management envisages a systematic and scientific approach towards conservation, harvesting, proper utilization and safe disposal of flowing water from the moment it strikes the land surface as a tiny drop till it joins the ocean for optimum production on sustained basis. After the successful implementation of Operational Research Projects by Central Soil & Water Conservation Research & Training Institute, Dehradun in 1970's, the Government of India launched a massive National Watershed Development Programme for Rainfed Areas in 1991. Many other programms funded by national and international agencies followed this. By the end of IXth Five Year Plan, an expenditure of INR 92.7 billion has been incurred in watershed programes by the Ministries of Agriculture and Rural Development covering an area of 29M ha. By the end of XIIIth Plan, it is envisaged to cover an area of 88.5M ha under watershed development programs at an estimated cost of INR 727.50 billion. With the shift in paradigms, participatory watershed management ensuring transparency and equitable sharing of resources and benefits among different stakeholders is being emphasized. Thus, watershed based development has been accepted as a single-window strategy for harmonizing simultaneously joint management of land, water, vegetation and human resources for sustainable productivity.

Water harvesting and its utilization is one of the major components of the watershed development programs which is realized through: (a) in-situ rain water harvesting measures, (b) surface water development measures, such as ponds, earthen reservoirs, small harvesting tanks, gully control structures and, drainage line treatments (c) sub-surface or ground water development measures such as percolation tanks, ponds, sub-surface dams, barriers, and, diaphragm dams (d) roof top collection and runoff water cistern and, (e) improved water management practices including micro-irrigation and on-farm water management. It has been estimated that about 24M ha-m rainwater can be harvested into water storage structures, of which one fourth can be harvested into ponds and percolation tanks in rainfall zone upto 1000 mm/annum. This runoff water can provide life saving irrigation of 5 cm each for more than 60-percent of the rainfed area in the country. Apart from providing water storage for supplementary irrigation, the integrated watershed

development programs help in moderating the floods in down stream areas and improve in-situ moisture conservation for increased biomass production. Besides, ground water recharge and rise in water table up to 2-meter height due to integrated watershed management were experienced in different regions of India with tremendous environmental externalities.

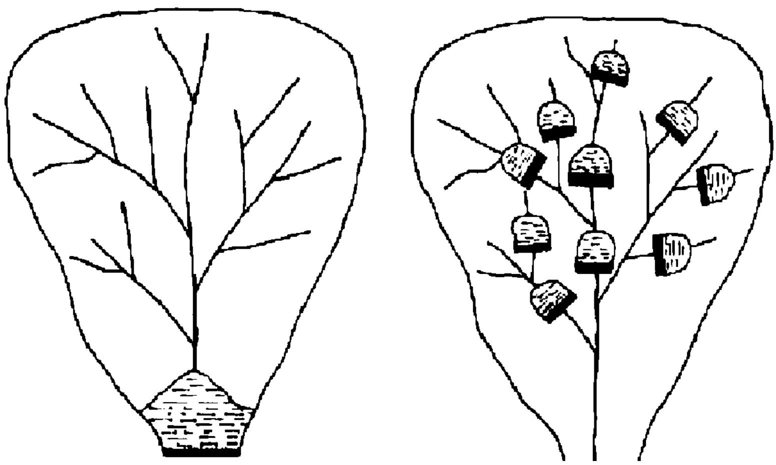
With an investment of INR 92.7 billion during IXth Plan, an additional area of 40,299 ha was brought under irrigation and most of the dug wells and tube wells have been rejuvenated with round the year water availability. However, the effect of water harvesting structures on ground water recharge has not been properly understood except by employing crude methods of studying rise and fall in water table of open or tube wells in different regions. A core project to analyze the relationships between water harvesting structures and ground water recharge in different agro-ecological situations has been initiated recently by CSWCRTI, Dehra Dun. The preliminary results in one of the watersheds at Antisar in Kheda district of Gujarat have shown that about 6.5 percent of the annual rainfall is effective in recharging the ground water aquifer. It was further observed that a minimum of 103.6 mm runoff is needed to trigger 1.0 mm of potential recharge in this agro-climatic setting. The results were obtained by employing water table fluctuation and chloride mass balance methods, which need further investigations and comparison with other modern tools and techniques for arriving at logical conclusions.

Introduction

Why does water-harvesting matter more today than any other time? There are several reasons (Jackson et al., 2001): (1) over half of the accessible freshwater runoff globally is already appropriated for human use; (2) more than one billion people currently lack access to clean drinking water and almost three billion people lack basic sanitation services; (3) because the human population will grow faster than increase in the amount of accessible freshwater, per capita availability of freshwater will decrease in the coming century; (4) climate change will cause a general intensification of the earth's hydrological cycle in the next 100 years, with increased precipitation, evapo-transpiration, occurrence of storms and significant changes in bio-geochemical processes influencing water quality. Human society now uses 26% of the total terrestrial evapotranspiration and 54% of the runoff that is geographically and temporally accessible. New dam constructions could increase accessible runoff by about 10% over the next 30 years, whereas the population is projected to increase by more than 45% during that period (Postel et al., 1996). Under such circumstances, *in-situ* rainwater harvesting shall be crucial.

As summers get hotter, and anthropogenic climate changes exert further strain on socio-economic and natural systems, water scarcity is likely to grow in regions such as South Asia and elsewhere. Addressing water problem holds the promise in future for a world compounded by climate change, growing population, and decreasing water-impounding area of traditional tanks due to urban and industrial settlements. In addition, extreme bio-climatic events are registering a monotonically increasing trend. A significant proportion of the global land area has been increasingly affected by a significant change in climatic extremes in the recent past.

A recent study projected, that in India, winter rainfall may decline by 5 to 25% and may lead to droughts during the dry summer months in coming decades (Lal et al., 2001). Thus, we will have to take into account the large-scale, natural climate variations as well as human-induced climate change in the management of natural, social and economic systems. If extreme climate events increase in future due to climate change, human society will use different means of adaptation. Additionally, regardless of climate fluctuations, population growth will put extra stress on natural resources. Alternative to ecologically damaging, socially intrusive, and capital-intensive water management projects that fail to deliver their desired benefits, it would be useful to invest in decentralized facilities, efficient technologies and policies, and human capital to improve overall productivity rather than to find new sources of water supply. Such efforts would need to be encouraged with innovative policy regimes that concurrently promote rainwater harvesting. Traditionally, such systems have been integrated with agro-forestry and ethno-forestry practices, and remain useful in contemporary conservation and ecological restoration of degraded ecosystems (Pandey, 2002). A systematic support to local innovations on rainwater harvesting could provide substantial amounts of water. Simple indigenously adapted techniques such as ponds and earthen embankments can help in harvesting and storage of rainwater. Rural and urban water use, restoration of streams for recreation, freshwater fisheries, and protection of natural ecosystems are all competing for water resources earlier dedicated only to food production. Decentralized rainwater harvesting adaptations (Figure 1) therefore become crucial for meeting the competing needs for water. For instance, in the Negev Desert, decentralized harvesting of rainwater in micro-catchments from rain falling over a 1-ha watershed yielded 95,000 litres of water per hectare per year, whereas collection efforts from a single large unit of a 345 ha watershed yielded only 24,000 litres per hectare per year (Pandey, 2001). Thus, 75% of the collectible water was lost as a result of the longer distance of runoff.



(a) (b)

Figure 1. Schematic of types of rainwater harvesting adaptation (a) case of single structure at the remote outlet, (b) decentralized water harvesting structure based adaptations

Traditional systems would become more efficient if scientific attempts are combined to enhance productivity of local knowledge. But some local technologies may already be at par with scientific attempts. Rainwater harvesting also has great potential as a solution to mitigate wide spread arsenic poisoning (Mandal et al 1996). In West Bengal and Bangladesh, alluvial Ganges aquifers used for public water supply are polluted with naturally occurring arsenic, which adversely affects the health of millions of people by causing arsenicosis (Pandey et al., 1999) and increasing the risk of cancer. Millions of people are at risk in Bangladesh alone (Dhar et al., 1997). Arsenic mobilization is associated with the advent of massive irrigation pumping that draws relatively young water directly into the aquifer (Harvey et al., 2002). Deep wells are being advocated as a remedy, that may provide a source of clean water; but the solution is only a provisional one. Rainwater harvesting is a better option to provide arsenic-free, safe water in a cost-effective and accessible manner, particularly for drinking and food preparation. We must, however, address several challenges to make rainwater harvesting efficient, particularly treatment of harvested rainwater in areas where pollution is rampant (Naik et al., 2002).

Water Harvesting and Integrated Watershed Management

Rainwater harvesting can be promoted as a core adaptation strategy for achieving the global security and sustainability of water resources in an era of anthropogenic climate change. However, this requires an insightful policy. Over thousands of years, people living in various geographical and climatic regions of the world have evolved diverse, indigenous rainwater harvesting and management regimes as an adaptation to climate change. Some of these practices continue to remain in use, particularly in South Asia. Rainwater harvesting in South Asia differs from that in many parts of the world – it has a history of continuous practice for at least the last 8000 years (Pandey et al., 2003). Water has been harvested in India since antiquity, with our ancestors perfecting the art of water management. Many water harvesting structures and water conveyance systems specific to the eco-regions and culture has been developed. Civil society institutions and government agencies are increasingly taking up water harvesting projects in rural areas. There are several initiatives where the traditional water harvesting practices have been modified depending upon the domestic and irrigation needs of the local community. Such improvisations initiated by the communities in different parts of the country and eco-region (Figure 2) is more scientifically adaptable. A few of them are listed in Table 1.

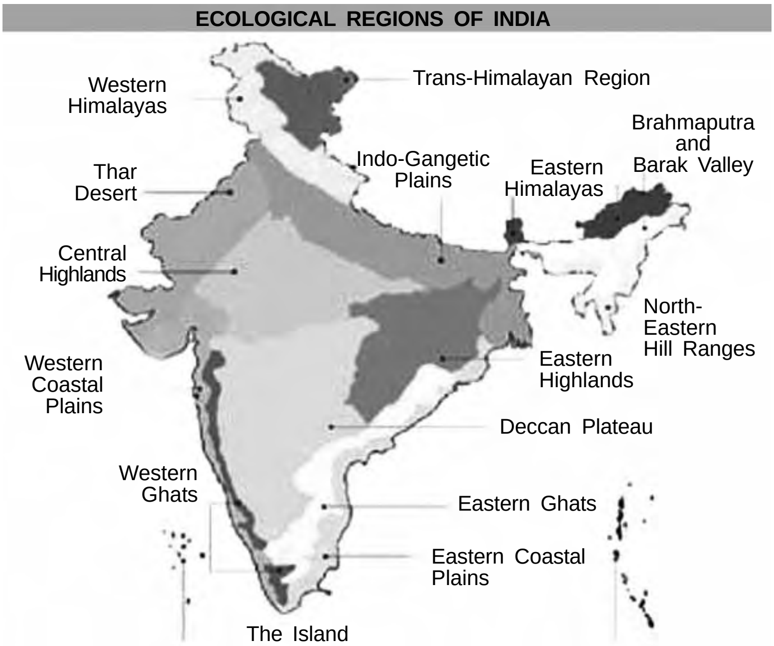


Figure 2. Ecological regions of India
(*Source: http://www.rainwaterharvesting. org/eco/eco-region.htm)*

Table 1. Traditional and contemporary water harvesting systems practiced in different agro-ecological zones of India

Ecological regions of India	Traditional water harvesting practices	Contemporary water harvesting systems
Trans-Himalayan region	Zing	Artificial glaciers
Western Himalaya	Kul,Naula, Kuhl, Khatri	—-
Eastern Himalaya	Apatani	—
Northeastern hill ranges	Zabo, Cheo-oziihi, Bamboo drip irrigation	—
Brahmaputra valley	Dongs, Dungs/jampois	—
Indo-Gangetic plains	Ahars-pynes, Bengal's Inundation channels, Dighis, Baolis	—
Thar Desert	Kunds/kundis, Kuis/beris, Baoris/bers, Jhalaras, Nadi, Tobas, Tankas, Khadins, Vav/Vavdi/Baoli/Bavadi, Virdas, Paar	Nadis, Polymer Kundis
Central highlands	Talab/Bandhis, Saza Kuva, Johads Naada/bandh, Pat, Rapat, Chandela tank, Bundela tank	Chaukas
Eastern highlands	Katas/Mundas/Bandhas	Jaldhar Models
Deccan plateau	Cheruvu, Kohli tanks, Bhandaras, Phad, Kere, The Ramtek Model	Tudum/Monga Network-ing of farm ponds
Western ghats	Surangam	—
Western coastal plains	Virdas	—
Eastern ghats	Korambu	—
Eastern coastal plains	EriOoranis	Horizontal roughening filters
The Islands	Jack Wells	—

(Source: http://www.rainwaterharvesting. org/eco/eco-region.htm)

Water harvesting has to be done on watershed basis, as watersheds are natural hydrologic units. Management of water resource done in this way is more effective. Watershed is characterized by many parameters such as land use, soil, hydro-geomorphology, and morphometric characteristics among others. Output from similar watersheds is often similar. With a suitable structure it is possible to harness maximum amount of water from the watershed. Location and type of structures depend upon soil, land use: land cover, drainage pattern, and geomorphology among others.

Integrated watershed management programs often envisage a holistic approach on development of water resources. This way *in-situ* water harvesting in the way of decentralized networks of water harvesting structures often prove to be more effective in augmenting groundwater recharge. Qualitative and quantitative information on the rise of water table consequent upon a successful implementation of watershed management program is a key for impact assessment. There are many case studies, which demonstrate that water harvesting for aquifer recharge is a great success (Table 2)[1]. They benefit from being low energy requiring and sustainable systems that can provide a long term supply of high-quality water without the need for modern technology. However, there are also different reasons due to which the various systems described wouldn't be effective, especially if they are not well planned prior to construction or if they are not maintained.

Table 2. Effect of watershed management strategies on groundwater recharge in different regions of India

Watershed	Surface storage-capacity created (ha-m)	Observed rise in groundwater table, m
Bazar Ganiyar (Haryana)	79.0	2.0
Behdala (H.P.)	18.0	1.0
Bunga (Haryana)	60.0	1.8
Chhajawa (Rajasthan)	20.0	2.0
Chinnatekur (A.P.)	5.6	0.8
GR Halli (Karnataka)	6.8	1.5
Joladarasi (Karnataka)	4.0	0.2
Siha (Haryana)	42.2	2.0

Source: Samra, 1997.

To state the obvious, water harvesting for augmenting groundwater recharge are only suitable in areas where aquifers exist. The recharge process is much simpler where unconfined aquifers exist and simple damming techniques, with percolation, can be used. It is important to carry out a thorough survey prior to selecting the site and deciding on the method of recharge. To analyse all the affecting themes and come up with a solution for water harvesting, resource information and decision support systems are the essential needs. Knowledge about the following parameters is critical to ensure proper placement of water harvesting structures to augment and ameliorate the aquifer:

[1]See Samra (1997) for further details.

- climatic records- rainfall, humidity, evaporation rates;
- topographical maps including drainage networks and ephemeral streams;
- data on soil thickness (types and distribution);
- distribution of rock types, especially surface features;
- definition of pore networks;
- recognition of recharge, discharge areas and the flow direction of the groundwater.

Moreover, series of studies have been conducted world wide to establish both diagnostic as well as prognostic interaction between the surface and groundwater processes. However, only few studies could address the realistic solution to the impact of water harvesting structures on groundwater recharge. To address this issue efforts have been made by CSWCR&TI, Dehradun to formulate a core project on the field scale monitoring of watersheds implemented under Integrated Wasteland Development Program (IWDP) funded by Ministry of Rural Development, Government of India. The regional centre at Vasad was the first among all the cooperating centres, which had initiated this project at Antisar in Gujarat. The project has become a classical effort in successful implementation of water harvesting technologies for groundwater recharge.

Water Harvesting Experiences: A Case Study (Antisar, Gujarat)

In Antisar a watershed development program was undertaken by focusing on water harvesting and artificial recharge structures. Antisar is located in Kapadwanj taluk of Kheda district in Gujarat. The findings from the program shows that the benefits accrued are worth the capital investments incurred on program activities. Twenty-three (23) artificial recharge filters and 16 check dams were constructed in the span of five years between 1998 to 2003 (Figure 3). Renovation and deepening works with five water-harvesting structures were also carried out. 139 tube wells/ open wells have been used to monitor the trend of water table rise or fall during the year 2002 and 2003. The salient findings of the studies are as under (Kumar et al., 2004):

Water Table Increase in Influence Zone of Water Harvesting Structures

The incidence of successive drought years (1999-2001) had resulted in reduced water table situation in the area. Therefore, between 1999-2001 the people in the watershed could not go for *Rabi*(winter) crops in a large scale due to early drying of the wells. Most of the recharge or water harvesting structures were constructed during the year 2001-2002 under the IWDP program. The influence of water recharged from different water harvesting structures such as check dams, recharge filters and ponds was studied using storage volume fluctuation technique in the area. It was observed that the average days that the water percolated from ponds and check dams would reach groundwater table in approximately 6 days, where as for the recharge filters it took one or two days.

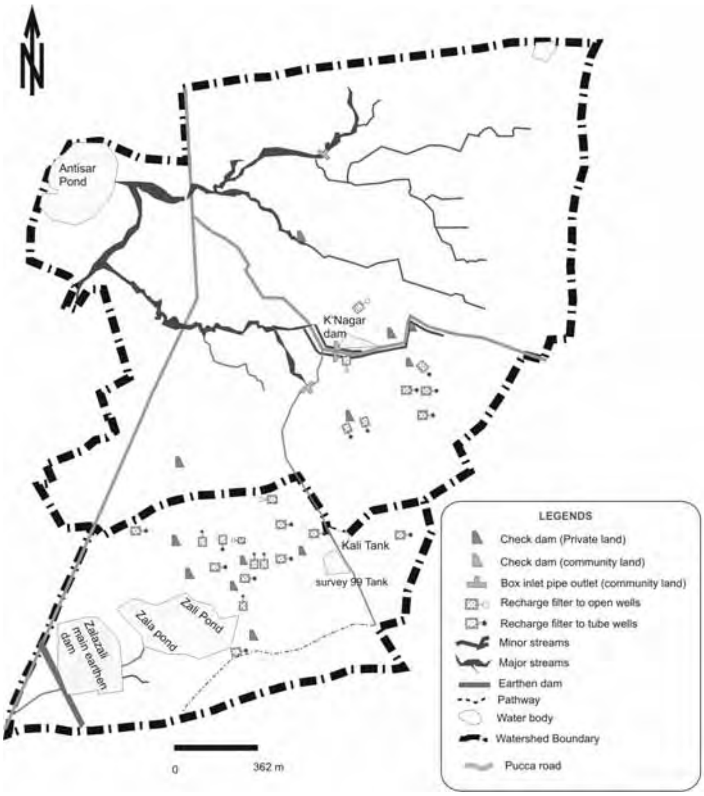


Figure 3. Details of the water harvesting structures in the Antisar watershed

The ground water mound under a structure recedes in 15 days to attain a dynamic equilibrium with the water table. The influence was found to be higher in the down stream side well of the water harvesting structure with a differential water table gain from 3.62 m to 10.66m.

Number of Wells Influenced

Based on the water table data recorded between July 20- August 5, 2004, 101 tube wells/open wells (73%) out of the designated 139 tube wells / open wells got influenced by the recharged water. The rainfall during this period was 234 mm. The net rise in water table during this period was 4.99 m.

In the successive fortnight (August 5-20, 2003) there was no rainfall. Therefore, the net rise in water table was 0.69 m, which is due to percolation of water from water harvesting structures coupled with internal distribution of water in the aquifer and gradual recession of the mounds formed under different water conservation structures (check dams, water harvesting ponds or recharge filters). By this time, almost all tube wells and the recharged water influenced open wells in the watershed. Therefore, it was observed that due to increased water harvesting at strategic positions, a better distribution of water occurs in the watershed.

Increase in Well Recharge Rate

Considering the rate of rise per unit of rainfall depth, about 23 per cent increase in recharge rate has been estimated during 2003. This is due to relatively more permeable characteristics of the recharge filter units that contribute better to the ground water table rise as compared to the more time consuming natural recharge from water harvesting structures which were present before the inception of the project.

Pumping and Recuperation Hours

The farmers in the Antisar watershed area are in the habit of withdrawing water in a whimsical and indiscriminate manner. The time of pumping water from the wells depends on the availability of the electricity, which is supplied in a fixed slab of eight hours a day. The pumps are attached with an auto timer unit that starts the pump the moment electricity is available and runs until the end of the duration of the supply hours. This implies a fixed pumping rate of 8 hours and 16 hours of recuperation until the next pumping. The rate of recuperation of the aquifer is estimated to be 0.101 m/day. When the water table is high, the time for recuperation to the initial level is approximately 8 hours after pumping for 8 hours continuously. This is due to the fact that a relatively more permeable fracture units (Fractured murrum with amygdaloidal basalt) near the ground surface (8 to 20m below the ground surface) results in faster water movement to the wells (Sena et al., 2003).

Increase in Irrigated Area

Compared with the area under *rabi* during 2000-01 and 2001-02, which was only 16.05 and 1.08 ha, respectively, a command area of 30.51 ha (total 71 ha including summer and *kharif*) has been brought under irrigated agriculture in rabi season with crops having intense water requirements. A total of 342 irrigations (including 120 supplemental irrigations during *kharif* and summer in the drought year) have been applied (irrigation number varying from 1 to 15) which is a major contribution of the ground water recharge works carried out in the area even though 2002 was a drought year. The total amount of water utilized for irrigations during 2002 was worked out as 1663 ha-cm assuming the depth of irrigation as 5 cm out of which summer and *kharif* accounts for a supplemental irrigation of 646 ha-cm.

The potential recharge / percolation from major water harvesting structures (Table 3) was measured during the water availability period. The recharge from these percolating ponds was estimated for the years 2001 to 2004 (Table 4).

It was found that in a watershed, a minimum of 103.6 mm rainfall is required to induce a one- mm potential recharge of the aquifer. The rainfall that induces maximum recharge (12.07%) in the watershed amounts to 714.4 mm. These may be reckoned as indices for comparison of different water harvesting structures in a particular area or extended to study the behavior of water harvesting structures in different agro-ecological zones (Sena et al., 2003).

The total recharge in the Antisar watershed is 6.33% of the annual rainfall (864 mm) and amounts to 4436.94 ha-cm using storage volume fluctuation method

Table 3. Specifications of major water harvesting structures in the study area

Sl.No.		Structure capacity, ha-m	Catchment area, ha	Ponding area, ha
1.	Zalazali E/D	163.00	9.40	10.13
2.	Zali pond	100.80	6.42	10.33
3.	Zala pond	43.20	8.99	10.80
4.	Antisar	612.00	4.50	11.27
5.	Khodiar nagar	7.48	0.83	0.41
6.	Kali tank	2.38	1.37	3.73
7.	Survey 99	1.06	0.61	0.58

Source: Sena et al, 2003.

Table 4. Volume of water recharged (R_e in cu-m) due to seepage from water harvesting structures/ponds for years 2001- 2004

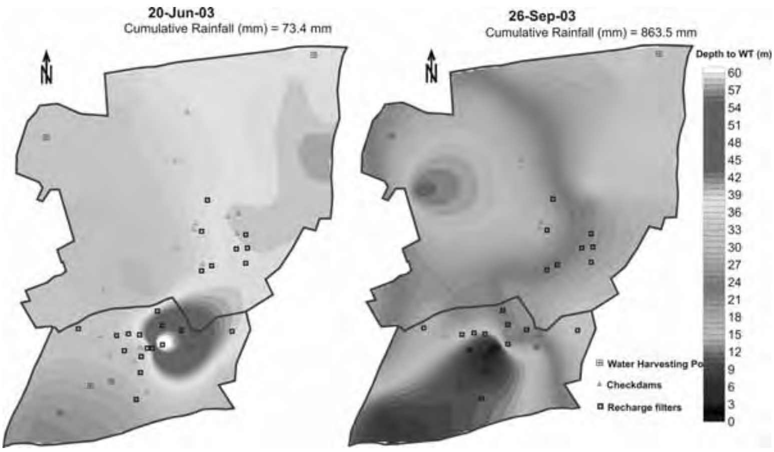
Sl.	Water harvesting	R_e (cu-m)			
No.	structure/pond	2001	2002	2003	2004
1.	Zalazali earthen dam	33919	77646	120803	89466
2.	Zali pond	51932	28562	83273	81568
3.	Zala pond	32833	80611	107065	92493
4.	Antisar main pond	48999	4673	53606	39128
5.	Khodiyarnagar pond	3210	795	1307	2151
6.	Kali Tank	—	—	11617	10116
7.	Survey 99	—	—	3048	3683
Total (cu-m)		170893	192287	380719	502914
Rainfall (mm)		421	538	864	826

*4 years average (Long term annual average (1983-2004) is 835 mm)
Source: Sena et al., 2003.

during 2003 (Figure 3), where as during 2004, the total recharge in the watershed is 8.024% of the annual rainfall (826 mm) and amounts to 5381.61 ha-cm (Figure 4). This recharge includes both direct recharge to the aquifer from recharge filters and potential recharge quantities from water harvesting structures.

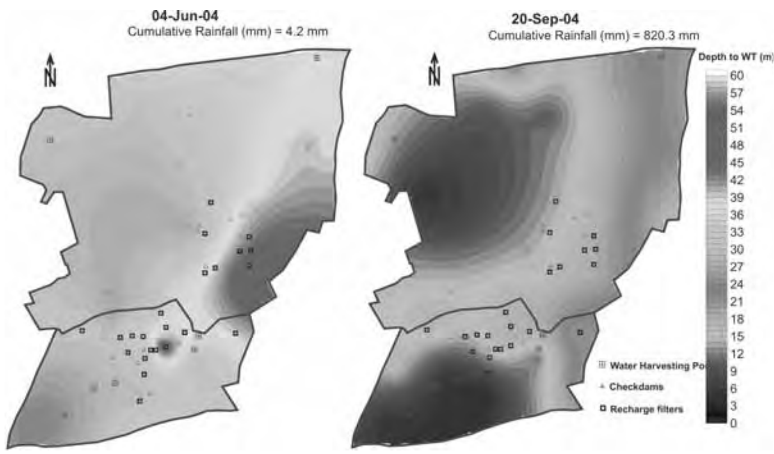
Water Quality Studies in the Watershed as Affected by Groundwater Recharge

It was observed during 2003 that the quality of water (from irrigation perspective) was found to be better in the area having recharge structures (Figure 5). The better quality class C_2S_1 has gained an area of 326.1 ha after the monsoon from a mere 60.9 ha before monsoon. The poorer quality classes C_3S_3 and C_4S_2, which had an aerial extent of 3.2 ha and 13.8 ha, respectively, were found to disappear after the monsoon. The predominant quality class of the watershed was C_3S_1 (Table 5).



(a) Pre-monsoon (b) Post-monsoon

Figure 3. Pre-monsoon and post-monsoon (2003) groundwater table scenario of the watershed (Source: Sena et al., 2003)



(a) Pre-monsoon (b) Post-monsoon

Figure 4. Pre-monsoon and post monsoon (2004) groundwater table scenario of the watershed. (Source: Sena et al., 2003)

Table 5. Change in water quality class and their areal extent before and after the recharge period

Class	Pre-monsoon		Post-monsoon	
	(%)	Area (ha)	(%)	Area (ha)
C_1S_1	0.0	0.0	0.1	0.4
C_2S_1	7.5	60.9	40.2	326.1
C_2S_2	0.8	6.5	0.2	1.2
C_3S_1	35.7	289.9	44.6	361.8
C_3S_2	53.9	437.7	15.1	122.5
C_3S_3	0.4	3.2	0.0	0.0
C_4S_2	1.7	13.8	0.0	0.0

Source: Sena et al., 2003.

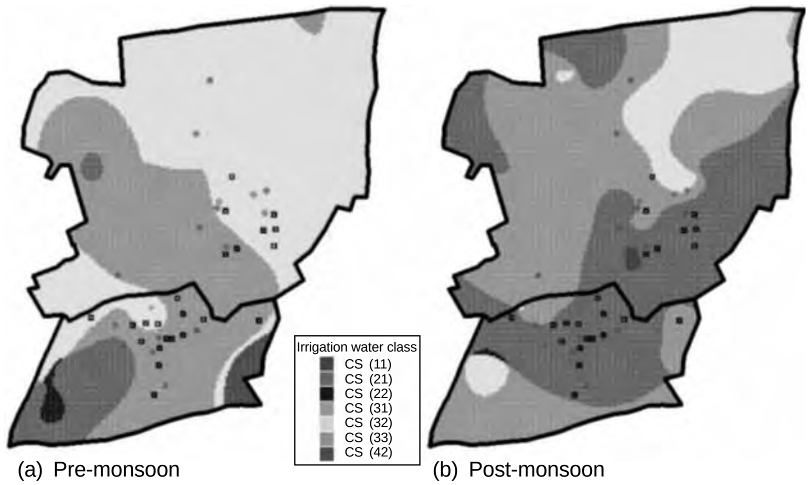


Figure 5. Irrigation water quality as affected by groundwater recharge during 2003. The rectangular symbols depict the recharge filters and the circular 'dots' represent the water harvesting check dams (Source: Sena et al., 2003)

Conclusions

Integrated watershed development programs (IWDP) promote *in-situ* water harvesting through decentralized network of water harvesting structures as exemplified by the case study in Antisar watershed. Efforts have been made to critically appraise the characteristics of water storage structures in relation to their position and size. The case study also shows the impact of water harvesting structures on inducing the potential recharge. The effect of various water harvesting activities comprising both direct and indirect recharge techniques on the quantity and quality of water has also been analyzed.

The IWDP initiatives not only augment the groundwater recharge but also improve the water quality of the aquifer. Adopting the methods undertaken in Antisar case study can only check the alarming rate at which the water table is declining. It is important to note that the recharge by a structure is limited to a certain maximum value; hence the recharged water should be used judiciously and sparingly.

Once a suitable site is selected to build the structure, it is very important to involve the local community in the construction of the structures. The community involvement would ensure sustainability of the system in the long run. Groups of local people need to be put in charge of the system to ensure that water is equitably distributed amongst all the stakeholders. Further, contrary to natural water harvesting techniques, when rainwater is being injected straight into the aquifer system, there may be severe consequences if the injected water is contaminated, as this may contaminate the good quality water already stored in the aquifer. Therefore, proper filter to trap any debris and a suitable water treatment plan, if necessary, is a must before allowing the water to enter the groundwater system.

Eco-efficiency alone cannot meet our water resources appetite following current utilization patterns. Utilization is a key to understanding the policy challenges as it focuses on our ever-increasing demands for water. One very important factor that also needs to be considered is to look into the consequences of storing the water upstream and its impact on communities downstream. If the downstream communities rely heavily on the surface waters for their survival, storing of water in the upper catchments may lead to social conflicts. Hence, water harvesting should be based upon realistic requirements and consumption patterns to meet the basic needs of people in a harmonious manner. Close look at consumption pattern will illustrate vividly that poor not only consume less water but they also pollute little. Investigation about consumption can tell a great deal about problematic relationship between economic growth and satisfaction of basic needs and human aspirations.

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Simulation Modeling and Optimization Studies for the Groundwater Basins of Northwest India: Case Studies and Policy Implications

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Abstract

There has been spectacular enhancement in agricultural production in northwest India during the last few decades. This could be possible due to adoption of high yielding crop varieties and fertilizer use coupled with indiscriminate exploitation of groundwater resources which has led to problems of declining water table, deterioration of groundwater quality, water logging and soil salinity in many parts of northwest India. This scenario of falling/rising water table is threatening the sustainability of agriculture in this food bowl of India. In order to study various strategies and frame policies for the management of water resources, it is necessary to assess the impact of human interventions on groundwater system through water balance studies and various models. In this paper application of simulation and optimization modeling has been discussed for ground water basins of northwest India. Case studies covering irrigated areas of Punjab and Haryana have been presented to demonstrate the usefulness of these models for developing strategies for sustainable agriculture. The studies indicate that if the present trend of excessive pumping of groundwater through installation of various structures continue, it will not be possible to pump groundwater by centrifugal pumping system because of declining water table at a very fast rate. The farmers will have to install submersible pumps at a very high cost in order to irrigate the field crops. In case of rising water table situations, the adoption of consumptive use practice of surface and poor quality groundwater coupled with efficient irrigation application system can help in sustaining the agricultural production in these regions. Policies for management of ground water resource on sustainable basis have also been discussed.

Introduction

In India, significant emphasis is being laid to increase the agricultural production in order to meet the food and fiber needs for the increasing population of the country. In order to meet the enhanced demand, the agricultural technology is being updated by adopting high yielding crop varieties and increasing fertilizer use, coupled with indiscriminate exploitation of groundwater resource which has led to problems of declining water table, deterioration of groundwater quality, water logging and soil salinity in many parts of the country especially northwest India. This scenario of falling/rising water table is threatening the sustainability of agriculture and is creating unsavory situation for the planning and administrative authorities. Current scenario warrants that a greater emphasis is laid on using the available water resources most scientifically and efficiently so that the country is saved from a very difficult situation and ensure food security for all.

In order to study various strategies and frame policies for efficient management of water resources, it is necessary to assess the impact of human interventions on groundwater systems through water balance and various modeling studies.

Case Study of Southwest Punjab

Water table has been progressively rising in almost all the districts of southwest Punjab due to inadequate drainage system, excessive application of water through canal irrigation and under-exploitation of groundwater resource due to its poor quality. To improve and sustain the agricultural production of the area afflicted by water logging and soil salinity, it is necessary to prevent further deterioration and reclaim the area already rendered waterlogged and saline by proper groundwater development in conjunction with canal water.

The joint use of simulation and optimization techniques to determine the optimal development and operation of ground water system is becoming an important and powerful tool (Gorelick, 1983; Yeh, 1992; Ahlfeld and Manoucherhr, 1994; Aggarwal et al, 2004). One such method to couple simulation model of particular groundwater system with an optimization model is the embedding technique, in which finite difference or finite element approximations of governing groundwater flow equations are introduced in linear programming model having a set of constraints. The groundwater variables are included as decision variables in the linear programming formulation. Conjunctive water use and management policies in southwest Punjab to control the rising water table using simulation-optimization approach have been developed.

Study Area

The study area is part of the Indo-Gangetic basin. The area lies between latitude 29°55′34″N and 31°09′47″N and longitude 73°50′31″E and 74°58′38″E and located in Ferozepur, Muktsar and Faridkot districts covering an area of about 6, 51,079 hectare. The region is bounded on western side by Sutlej river; toward south area is surrounded by Rajasthan boundary and toward east by Sirhind feeder (Fig.1) canal. The normal annual rainfall is 300 mm and almost 80 per cent of rainfall takes place in *kharif* season. The soils of the area are formed through alluvial deposits. In Muktsar and Ferozepur districts the soil is sandy. In Faridkot district, the soils vary from sandy loam to loamy sand. The major crops grown in area are rice, cotton and wheat. Irrigation is done by both canal and groundwater. The groundwater cell of the Department of Agriculture, Punjab and Water Resources Directorate of the Department of Irrigation, Punjab have installed about 60 observation wells in the study area to monitor the depth of water table below ground surface. The observations are taken twice a year; the pre-monsoon water table is recorded in the month of June and post monsoon in the month of October.

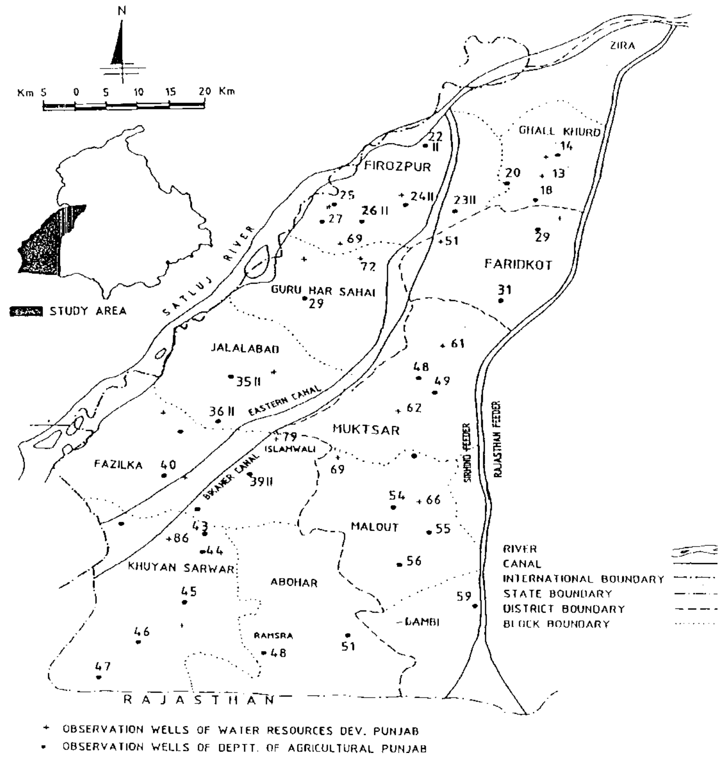

Figure 1. Location map of Southwest Punjab

Groundwater Simulation Model Inputs

A grid map having consistent grid spacing of 10 km x 10 km is superimposed over the map of southwest Punjab to discretize the area into cells (Fig.2). The boundary of the aquifer is approximated in a linear stepwise fashion. Based on the June/October water level data the water level contour maps are drawn. The grid map is superimposed on these maps to incorporate the values of hydraulic head at the center of each cell lying inside the study area. Same procedure is used to estimate the values of hydraulic conductivity and specific yield and bottom elevation of aquifer for each cell. For computing the source/sink terms, the recharge and draft values were distributed to various cells. The block wise groundwater draft and recharge was distributed to each cell falling in the block according to the area of that cell in the block.

Water Resources Allocation Model Inputs

The inputs to the water resources allocation model include variables such as net irrigation water requirement of crops, canal and tube well water availability, and quality of groundwater. These are discussed as follows:

Net Irrigation Water Requirement of Crops

The net irrigation requirement of crops is the depth of irrigation water, exclusive of effective rainfall, carry-over soil moisture or ground water contribution. Since the rainfall is stochastic in nature, the effective rainfall and ultimately the irrigation requirements of crops also become stochastic. The rainfall data from 1986-87 to 1997-98 is used for fitting Gamma probability distribution and the value of rainfall at 95, 85 and 75 per cent probabilities has been determined. The effective rainfall at different probabilities is estimated using USDA Soil Conservation Service Method (Smith, 1992). Net irrigation water requirement of crops at 5, 15 and 25 per cent risk level has been determined by taking the difference of potential evapo-transpiration and effective rainfall.

Actual Irrigation Requirement of Crops

After computing net irrigation requirement, gross irrigation requirement was computed by dividing it with irrigation efficiency. Since quality of irrigation water is poor, so leaching requirement is also added to gross irrigation requirement (Rhoades, 1974).

Groundwater Pumpage

Groundwater pumpage depends upon the actual irrigation requirement, quality of groundwater and canal water availability.

Quality of Groundwater

Groundwater quality of study area has been divided in three categories viz. < 2.0, 2.0-4.0 and > 4.0 dS/m (Brar and Singh, 1993). For present study groundwater is divided into five categories namely < 2.0, 3.0, 4.0, 5.0 and 6.0 dS/m. The groundwater was used by mixing with canal water in such a proportion that the resultant EC is acceptable for the range of crops to be grown in the study area.

Water Allocation Model

A water allocation model is developed to maximize ground water pumpage considering the groundwater quality, actual irrigation requirement, canal water availability and hydraulic head. The decision variables of the model are groundwater hydraulic head and tube well discharges. The linear programming package is used for this purpose. The model is combined with simulation model.

Objective Function

The objective function is to maximize tube well discharge at all the active nodes. The maximum discharge is given by equation:

$$\text{Max } Z = \sum_{i=1}^{14} \sum_{j=1}^{11} Q_{i,j} \qquad (1)$$

where,

Z = Total discharge at all the nodes, $Q_{i,j}$ = Tubewell discharge at *i*th row and *j*th column

i = Number of row and j = Number of column

Constraints

To achieve the above objective the following constraints have been considered.

(i) Groundwater flow equations: For unconfined homogeneous aquifer two dimensional transient flow equation can be written as

$$\frac{h_{i+1,j}+h_{i,j+1}-4h_{i,j}+h_{i-1,j}+h_{i,,j-1}}{(\Delta x)^2}=\frac{s_{i,j}}{T_{i,j}}\left(\frac{h_{i,j}-h_{i,j,t=0}}{\Delta t}\right)+\frac{Q_{i,j}-r_{i,j}}{T_{i,j}} \qquad (2)$$

where,

h = hydraulic head (m), w = sink/source term (m/day), T = transmissivity (m^2/day)

r = recharge (m/day), Q= pumpage (m/day) and t = time, (day)

The system of algebraic linear equations at every grid point becomes a set of constraints and they insure that the groundwater variables are directly incorporated as decision variables in management model.

(ii) Groundwater pumpage: Groundwater used in each season must be less than or equal to the maximum groundwater potential available in that season (which depend upon the quality of groundwater, actual irrigation requirement and canal water availability)

$MQ_{i,\,j} = AIR_{i,j}*(EC_{mw} - EC_{cw})/(B_{i,j}* \ EC_{twi,j} - EC_{cw} + A_{i,j}\ EC_{mw})$ (3)

$Q_{i,\,j\,\pounds}\,MQ_{i,\,j}$ (4)

MQ = Maximum potential of groundwater at ith row and jth column.
AIR = Actual irrigation requirement (mm),
A = Fraction of safe tube well water
B = Fraction of unsafe tube well water
EC_{mw} = Electrical conductivity of mix water, dS/m
E_{Ccw} = Electrical conductivity of canal water, dS/m
$EC_{t/w}$ = Electrical conductivity of tube well water, dS/m

(iii) Hydraulic head constraints: Hydraulic head constraints at any/all nodes can be added in the model so that water level should not rise/fall under specified limit.

$h_{i,\,j\,<=}\,Ri,\,j - X$ (5)

$h_{i,\,j\,>=}\,Ri,\,j - Y$ (6)

X = upper limit of water table depth (m)
Y = lower limit of water table depth (m)
Ri, j = reduced level (m)

(iv) Evapo-transpiration(ET) constraints: Actual irrigation requirement was found at 90 percent level of ET at upper limit of pumpage was changed as the difference between the actual irrigation requirement and canal water availability at that node.

$Q_{i,\,j\,\pounds}\,AIR_{ET\%i,\,j} - CW_{i,\,j}$ (7)

where,

$AIR_{ET\%i,}$ = Actual irrigation requirement
$CW_{i,j}$ = Canal water availability

For developing optimal pumping strategies for controlling the rise in water

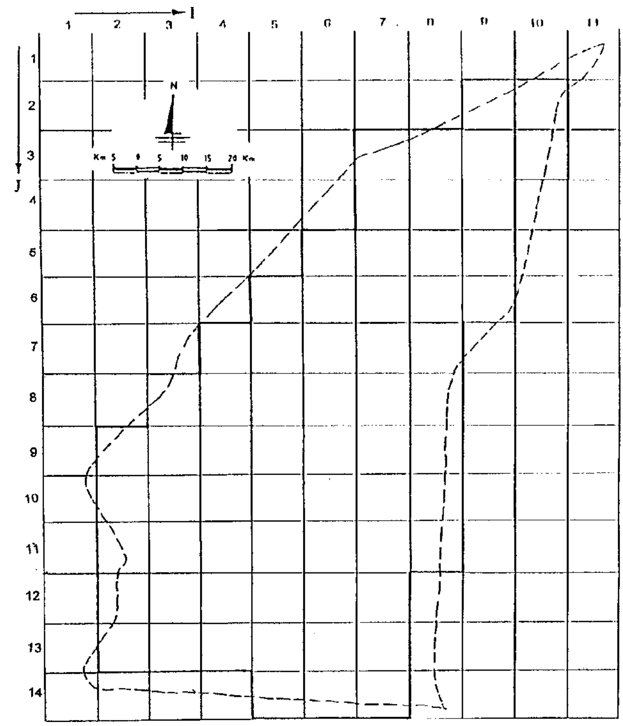

Figure 2. Discretization of aquifer of Southwest Punjab

table a number of simulation runs were carried out using the simulation-optimization model in which objective function was to maximize the pumping with a view to arrest rise in water table. The impact of management alternatives on water table depth was evaluated with reference to simulated groundwater conditions in southwest Punjab for June,1998. The following simulation runs were performed.

- *Simulation-optimization run one:* 100 per cent ET demand, maximum safe pumpage depending upon groundwater quality and actual irrigation requirement with no constraint on hydraulic head.
- *Simulation-optimization run two:* 100 per cent ET demand, maximum safe pumpage depending upon groundwater quality and actual irrigation requirement with hydraulic head constraint 3 to 10 meter below ground surface.
- *Simulation-optimization run three:* 90 per cent of ET demand, maximum canal water use, upper limit constraint on pumpage, no constraint on hydraulic head and 30 per cent of canal water available in Malout block distributed equally in Khuian Sarwar, Fazilka and Jallalabad blocks.

The impacts of different simulation optimization runs on groundwater regime are discussed below:

- *Simulation-optimization run one:* The model was run to predict the water levels in *rabi* and *kharif* seasons during next five years. A perusal of Table 1 and 2 reveal that the proposed management plan will require 134,743 ha-m of groundwater and 29,968 ha-m of canal water in *kharif* season. In *rabi* season this plan will require 201,277 ha-m of groundwater and 38,878 ha-m canal water to meet 100 per cent ET demand. These data also reveal that under this management plan the groundwater pumpage will increase to 134,743 ha-m from 60,413 ha-m (June 1998) during *kharif* and from 60,413 ha-m to 201,277 ha-m during *rabi* season. However, the canal water will remain under utilized to the extent of 57.8 per cent during *kharif* and 60.5 per cent during *rabi* season. Table 1 and 2 reveals that the proposed plan will result in sharp decline in water table over the entire southwest Punjab.

- *Simulation-optimization run two:* A perusal of data under Table 1 and 2 reveals that total groundwater pumpage decreased gradually from 129,104 ha-m to 96,652 ha-m for *kharif* season and from 187,105 ha-m to 92,405 ha-m for *rabi* season. The canal water requirement increases gradually from 35,607 ha-m to 68,059 ha-m during *kharif* seasons and 53,050 ha-m to 147,750 ha-m during *rabi* seasons. Under this management plan water table depth remains generally between 3 to 10 m below ground surface. Table 1 also reveals that during *kharif* the canal water supplies are sufficient to meet the ET demand. However, during *rabi* the canal water supplies fall short by 33,740; 47,211 and 49,167 ha-m in third, fourth and fifth year, respectively (Table 2). It will not be possible to meet the deficit during the *rabi* season even if the surplus canal water available during *kharif* is transferred to *rabi* season.
- *Simulation-optimization run three:* In this simulation run upper limit on groundwater draft was decided as the difference between the irrigation requirement and canal water supply at each node except for the nodes (9,5), (10,6), (10,7) (11,6) and (11.7). The nodes (10,6), (10,7), (11,6) and (11,7) fall in Malout block whereas node (9,5) falls in part of Muktsar, Fazilka and Jalalabad blocks. For these nodes the upper limit on groundwater draft was decided depending upon actual irrigation requirements and safe groundwater quality. After running the model for one year it was observed that there is a sharp rise in water table at nodes (6,6), (7,6) and (8,4) which falls under Guruharsahai and Jalalabad blocks. So upper limit of groundwater draft on these nodes were decided during *rabi* season on the basis of irrigation requirement at 90 per cent ET and available groundwater quality. Maximum pumpage was done on these nodes to arrest rise in water table for the next four *rabi* seasons by changing upper limit of groundwater draft.

A perusal of data under Table 1 and 2 reveal that the groundwater draft requirement remains 72,745 ha-m during all five *kharif* seasons and for *rabi* season it is 138,233 ha-m for the first rabi season and 140,518 ha-m for the next four *rabi* seasons whereas existing groundwater draft for the *rabi* season (ending June 98) is 60,413 ha-m. Data further reveal that canal water supplies are sufficient in both the seasons for all the five years. These data also reveal that water- logged area first increases from existing 94,470 ha to 165,961 ha during the first *kharif* season and then it reduces sharply to 17,873 ha during the first *rabi* season. During second *kharif* season it increases to 102,130 ha but during next four *rabi* seasons it remain zero and it reduces gradually to 91,917 ha, 63,831 ha and 35,746 ha in third, fourth and fifth *kharif* season. Table 1 reveals that area under water table depth greater than 10 meter was zero for first three years of simulation run but increased to

Table 1. Results of different management strategies for monsoon season

Year	Management strategies	Monsoon						
		CW[1] available (ha-m)	Pumpage (ha-m)	CW req. (ha-m)	Area under water table depth (ha)			
					<2m	2 to 3m	3 to 10	>10m
	JUNE, 98	98583	60413	71110	94470	168515	370221	17873
1st	SOR1*	71110	134743	29968	20426	114896	497884	0
	SOR2*	71110	129104	35607	5107	86810	559162	0
	SOR3*	71110	72745	71110	165961	76598	408520	0
2nd	SOR1	71110	134743	29968	0	0	385541	265538
	SOR2	71110	123468	41243	0	0	651079	0
	SOR3	71110	72745	71110	102130	61278	487671	0
3rd	SOR1	71110	134743	29968	0	0	117450	533629
	SOR2	71110	104432	60279	0	0	651079	0
	SOR3	71110	72745	71110	91917	30639	528523	0
4th	SOR1	71110	134743	29968	0	0	651079	638313
	SOR2	71110	98040	66671	0	0	651079	0
	SOR3	71110	72145	71110	63831	20426	520863	45959
5th	SOR1	71110	134743	29968	0	0	2583	648526
	SOR2	71110	96652	68059	0	0	651079	0
	SOR3	71110	72745	71110	71100	35746	477457	112343

*See footnote under Table 2, [1]CW = Canal water

Table 2. Results of different management strategies for winter season

Year	Management strategies	Monsoon						
		CW available (ha-m)	Pumpage (ha-m)	CW req. (ha-m)	Area under water table depth (ha)			
					<2m	2 to 3m	3 to 10	>10m
	JUNE,98	98583	60413	71110	94470	168515	388094	0
1st	SOR1*	98583	201277	38878	0	0	651079	0
	SOR2*	98583	187105	53050	0	0	651079	0
	SOR3*	98583	138233	77903	0	84257	548949	0
2nd	SOR1	98583	201277	38878	0	0	74044	577035
	SOR2	98583	146597	93558	0	0	651079	0
	SOR3	98583	140518	75619	0	74044	577035	0
3rd	SOR1	98583	201277	38878	0	0	20426	630653
	SOR2	98583	107832	132323	0	0	651079	0
	SOR3	98583	140518	75619	0	15320	651079	0
4th	SOR1	98583	201277	38878	0	0	2553	648526
	SOR2	98583	145794	145794	0	0	651079	0
	SOR3	98583	140518	75619	0	5107	536182	109790
5th	SOR1	98583	201277	38878	0	0	2553	648526
	SOR2	98583	92405	147750	0	0	651079	0
	SOR3	98583	140518	75619	0	0	485118	165961

*SOR1= Maximum pumpage, no constraint on head, 100% ET; *SOR2= Maximum pumpage, head 3 to 10m, 100% ET; *SOR3= Maximum pumpage and canal water use, no constraint on head, 90% ET

45,959 ha and 112,343 ha in fourth and fifth *kharif* season. During *rabi* season it increases to 109,790 ha and 165,961 ha in fourth and fifth season (Table 2).

The simulation optimization run results in area under water table depth < 2 m in Guruharsahai, parts of Jalalabad and Muktsar blocks where as declining water table trend was observed in Fazilka, Khuian Sarwar and Abohar blocks. The problem of area having water table depth < 2 m can be solved by increasing the pumping limit to maximum possible discharge limit.The declining water table area can be controlled by reducing the pumping in that area and meeting the remaining irrigation demand by transfer of canal water from rising water table area to declining water table area. Another alternative could be to decrease the pumping in declining water table area by shifting the cropping pattern so that irrigation requirements are reduced as compared to existing one. This can be achieved by decreasing the area under paddy in Fazilka, Khuian Sarwar and Abohar blocks.

Case Study of Sirhind Canal Tract

The Sirhind canal tract of Punjab comprises of four districts: Ludhiana, Patiala, Sangrur and parts of Ropar. Water table has been declining in most of the blocks in this tract for the last three decades. Out of the total irrigated area, seventy five percent is now irrigated by groundwater through tube wells, against 55% three decades ago. Because of excessive extraction of groundwater the water table is declining at the rate of 17 cm to more than 1 m per year. This has resulted in lowering of existing centrifugal pump sets deeper into the pits to meet their suction requirement or have been replaced by costly submersible pump sets. In order to develop various strategies for management of water resources in this tract a management model was developed and combined with simulation model using response matrix approach.

Groundwater Simulation Model

The two-dimensional groundwater flow equation was used to simulate groundwater flow in non-homogeneous, anisotropic aquifer. The Galerkin's finite element method with linear quadrilateral elements was used to discretize the groundwater flow equation in space. The region was sub-divided into 49 quadrilaterals having 73 nodes. Eigen-value solution of the resulting ordinary differential equation was obtained continuous in time (Kaushal and Khepar, 1988). The model was used to compute hydraulic head at nodal points and at the water level observation points being monitored by the Central Groundwater Board, State Water Resources Directorate and State Department of Agriculture (Fig. 3) The value of transmissivity varied from 700-2500 m^2/day and storage coefficient was 0.2. The expected value of recharge for part of the Sirhind canal tract (Fig. 3) was 74,692 ha-m, whereas the withdrawal for the year 1987-88 was 100,896 ha-m. There was a decline of water level at the rate of 0.18 to1.4 m/ year, the higher value of decline occurred in the central part of the tract.

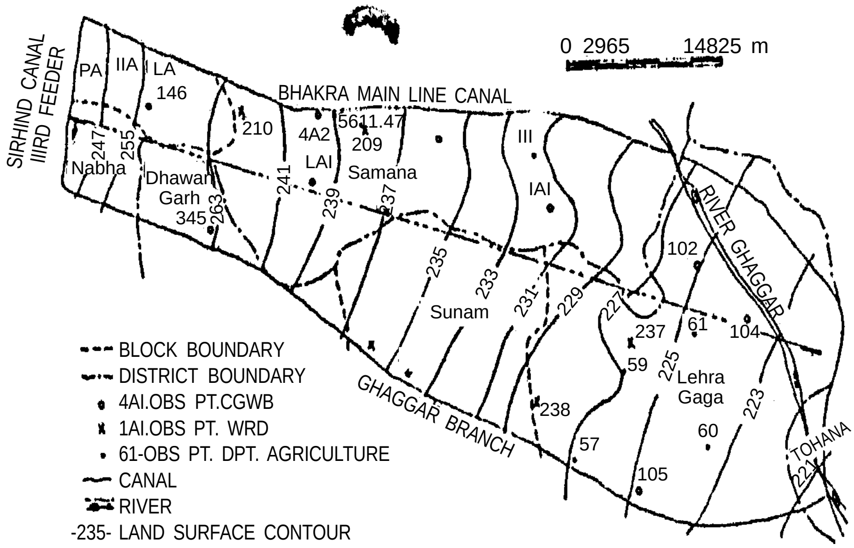

Figure 3. Study area showing land surface contours (m) and water table observation points

Management Model

A chance constrained linear programming model was developed (Kaushal & Khepar, 1992).

Objective function: The objective was to maximize annual net returns. The maximum net return (Max Z) is given by the equation:

$$\text{Max } Z = \sum_{S=1}^{2} \sum_{w=1}^{W} \sum_{k=1}^{K} NRswk \; Xswk - \sum_{S=1}^{2} CSs \; SWs$$

$$- \sum_{S=1}^{2} \sum_{n=1}^{N} CTsn \; TWsn - \sum_{n=1}^{N} PCTWn \,(NSLn + DHn - hn) \qquad (8)$$

where,

S = growing season (S=1 for winter season and S=2 for monsoon season);

W = level of water application, W=1,2,.. W; k = crop index, k=1,2...K; n = finite element, n=1, 2..

N; NRswk = net returns; Rupees/ha, above all variable production cost, excluding the cost of irrigation water, from crop k with level of irrigation water W in season S;

Z =total net returns, in Rupees over variable costs;

Xswk =area in ha allocated to crop k, grown with level of irrigation water W in season S;

CSsn = cost in Rupees for applying 1 ha-m of canal water in season S;

SWs = canal water in ha-m allocated at head of the field in season S;

CTsn = cost in Rupees for applying 1 ha-m of groundwater at node n in season S;

TWsn= groundwater in ha-m allocated from element n in season S;

NSLn = natural surface elevation (RL) in metres at node n;

DHn = dynamic head in meters at node n;
hn = hydraulic head elevation (RL) in metres at node n and
PCTWn = penalty cost weighting factor, Rupees/m of head, because of water level lowering at node n.

Constraints

(i) In applying the model, following constraints have been taken into consideration. Water allocation: Irrigation water requirements of crops must be met from canal and groundwater supply in season at a probability of b

$$P \{ \sum_{k=1}^{K} \sum_{w=1}^{W} \text{NIRswk Xswk} \leq \text{SWs} + \sum_{n=1}^{N} \theta\text{ct TWsn} \} \geq \beta \text{ for all s} \quad (9)$$

where,

NIRswk = irrigation water required in ha-m for crop k with irrigation level W in season S;
q = tubewell water conveyance efficiency;
P = probability operator;
b = probability level, 0 < bs £ 1
The deterministic equivalent to the probabilistic constraint when formulated in terms of chance constrained is:

$$\sum_{k=1}^{K} S^{-1}\text{swk} (\beta\text{s}) \text{ Xswk} \leq \text{SWs} + \sum_{n=1}^{N} \theta\text{ct TWsn for all s} \quad (10)$$

$^{-1}$swk (βs) is inversse distribution function of NIRswk for βs level of assurance.

(ii) Land area: The total area under various crops in each season cannot exceed the total available area for irrigation

$$\sum_{k=1}^{K} \sum_{w=1}^{W} \text{ALFAs Xswk} \leq \text{Tas for all s} \quad (11)$$

where
ALFAs = land area occupying coefficient for crop activity (ALFAs = 1, if the crop is grown in the season S, otherwise it is zero), and
Tas = crop land in ha available in season S

(iii) Canal water: Canal water allocated in season S cannot exceed canal water available in season S after allowing for all losses.

$$\text{SWs} \leq \text{ASWs} \qquad \text{For all S} \quad (12)$$

where,
ASWs = canal water in ha-m available in season S after allowing for all losses.

(iv) Tubewell water: Tubewell water allocated from element n cannot exceed tubewell water available in season

$$\text{TWsn} \leq \text{ATWsn} \qquad \text{for all s,n} \quad (13)$$

where,
ATWsn = tubewell water in ha-m available in season S.

(v) Minimum area:

$$\sum_{w=1}^{W} Xswk \geq MIARsk \text{ for all s and } k = 3,10,11,13 \quad (14)$$

where,
MIARsk = minimum area in ha required for crop k grown in season S.

(vi) Maximum allowable area:

$$\sum_{w=1}^{W} Xswk \leq MAALsk \qquad \text{For } s = 1;\ k = 5 \quad (15)$$

where,
MAALsk = maximum area in ha allowable to crop k grown in season S.

(vii) Hydraulic head : The hydraulic head in an element cannot exceed the hydraulic head elevation simulated by the groundwater model at node n

$$hn \leq hsmm \qquad \text{for all n} \quad (16)$$

where,
hsmn = hydraulic head elevation (EL) in meters simulated by groundwater model at node n.

(viii) Non-negativity :

$$Xswk \geq 0;\ Sws \geq 0;\ TWsn \geq 0;\ hn \geq 0 \quad (17)$$

Methodology

A tract in Sirhind Canal (Fig. 3) bounded by the Bhakra Main Line Canal, Ghaggar Branch, Sirhind Canal Third Feeder and River Ghaggar was used for application of the models (Figure 3). The tract lies between latitude 29° 38' 27'' N to 30° 24' 7''N and longitude 75° 51' 15'' E to 76° 15'E. The climatic conditions in the tract are, severely cold winters particularly in the month of December and January, and intense hot summers in April, May and June. Mean monthly air temperature during winter is 5° C whereas mean monthly air temperature in the summer reaches 40° C.

The groundwater simulation model was calibrated and validated for prediction of groundwater table by using observations for the period 1975 to 1987. The simulation model was used to determine the effect of unit responses in terms of groundwater withdrawal on hydraulic head. An assemblage of unit responses was included in the management model. Other inputs to the management model were net irrigation water requirement of crops at 5% and 25% risk levels (expected values of ET was taken as average of 30 years, rainfall was considered probabilistic, and, a two parameter gamma distribution was fitted to the monthly rainfall data), water resources availability, cost of irrigation water and net returns excluding the cost of irrigation water. Net irrigation requirements of crops were computed by diminishing effective rainfall (using USDA, SCS method) at 5% and 25% risk level, from the expected value of ET. Water application was considered at levels 1, 2, 3 and 4, which corresponds to water production functions at 25, 50, 70 and 100% of the net irrigation water requirement. Crop water production functions were developed based on experimental observations (Rajput, 1985). Four type of functions were used (Eqs. 18 to 21) namely Cobb-Douglas, quadratic, square root and Modified Mitscherlich-Spillman functions for wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), raya (*Brassica juncea*), gram (*Cicer ratinum),* potato (*Solanum tubersom),* berseem fodder (*Trifolium alexandrinum*), rice (*oryza sativa)*, cotton (*Gossypium arborium*), maize (*Zea mays*), sugarcane (*Saccharum offinarum*), groundnut (*Arachis hypoge*), green gram (*Phaseolus radiata*) and sorghum fodder (*Sorghum vulgare*)

Cobb-Douglas function

$$Y = a\ W^{b} \tag{18}$$

Quadratic function:

$$Y = a + bW + CW^{2} \tag{19}$$

Sqare-root function

$$Y = a + bW + cW^{0.5} \tag{20}$$

Modified Mitscherlich-Spillman functions

$$Y = a\ (1\text{-}e^{-b(w+c)}) \tag{21}$$

where,
Y = crop yield, q/ha; (1quintal=100 kg)
W = depth of water applied, cm and
a, b, c = constants

The crop yield is influenced by crop variety and soil fertility. However, these factors were fixed and only water applied was considered a variable. The soils were sandy loam. The available nutrients such as organic matter, P_2O_5 and K_2O varied from 0.162 – 0.308%, 1.8 – 13.2 and 51 – 113 kg/ha,respectively.

The model outputs are in terms of cropping pattern, canal water and groundwater allocation and hydraulic heads at nodes for maximized net returns. The depth of pumping cost of water, rain, price of crop and availability of land and water influence maximized net returns. In this study the hydraulic heads at nodal points were made a constraint in the management model. The cost of canal water and groundwater was Rs 240 and Rs 927 per ha-m of water, respectively. The annual rainfall was 38 cm at 75% probability level. Prices of crops prevailing in Punjab during the year 1988 were used. Total land resources of the study area were 115,803 ha. The annual canal water and groundwater resources available were 39,170 ha-m and 100,896 ha-m, respectively.

Water Production Functions

The best-fit water production functions based on statistical analysis are given in Table 3. The quadratic functions were selected for wheat, barley, raya, gram, rice, sugarcane, moong and sorghum fodder; square root functions for cotton, maize and berseem fodder; Modified Mitscherlich-Spillman functions for potato and groundnut crops.

Table 3. Crop water production functions

Sl.No.	Crop	Coefficients			R^2	F-value
		a	b	c		
Quadratic						
1.	Wheat	16.31263	1.034402 (5.65*)	-0.012068 (-2.6) NS	0.985	67.12*
2.	Barley	9.586905	0.654469 (2.55) NS	-0.009018 (-1.09) NS	0.972	17.58*NS*
3.	Raya	9.0495	0.212845 (1.83) *NS*	0.002534 (-.67)*NS*	0.957	11.11*NS*
4.	Gram	8.65822	0.2777529 (1.41) *NS*	-0.003947 (-0.62) *NS*	0.914	5.32*NS*
5.	Rice	-1.632408	0.357109 (2.78) *NS*	-0.000431 (-1.33)*NS*	0.998	294.40*
6.	Sugarcane	- 37.435425	9.717468 (7.27*)	-0.024837 (-5.18)*NS*	0.996	153.45*
7.	Green gram	- 2.08542	0.914279 (2.02) *NS*	-0.020513 (-1.74) *NS*	0.890	4.07*NS*
8.	Sorghum fodder	161.66644	7.125275 (2.16) *NS*	-0.055064 (-1.81)*NS*	0.947	9.08*NS*
Square root						
9.	Cotton	- 29.346767	-0.730293 (-1.32)*NS*	12.418518 (1.79)*NS*	0.974	18.89*
10.	Maize	- 32.315575	-1.256317 (-48)*NS*	18.086426 (0.71)*NS*	0.945	8.67*NS*
11.	Berseem fodder	20.887573	-10.78100 (-3.0)*NS*	182.26563 (3.47*)	0.979	23.92*
Modified Mitscherlich-Spillman functions						
12.	Groundnut	21.2	0.084569 (3.54*)	4.6319	0.862	12.54*NS*
13.	Potato	205.0	(0.082384) (1.84) *NS*	-28.3002	0.630	3.41*NS*

Note: ** The values in parentheses are t-values for the coefficients significant at 1% level of significance
* Significant at 5% level of significance
NS: Not significant at 5% level of significance

Optimization of Net Benefits

The results of management model combined with simulation model using response matrix approach were obtained at risk levels of 5% and 25% (95% and 75% probability of rainfall). The cropping pattern is given in Table 4. As the risk level increased from 5% to 25% the area under wheat and cotton at water application level 3 increased from 59,853 ha to 68,778 ha and 100,749 ha, respectively. Maize shifts to water application level 4. Rice and sugarcane that have a higher water requirement are deleted from cropping pattern. Canal water and groundwater were fully utilized. The hydraulic head remained at the levels predicted by the groundwater simulation model. As the risk level increased from 5 to 25% the annual net returns increased. The reason for this is, that with an increase in risk level, the irrigation water requirements of crops decreased. The model adjusts the allocation of land and water resources in such a way that more area is allocated to crops under higher levels of water application, thereby increasing annual net returns. The study did not consider labour as a constraint. However the results may be influenced if high value, labour intensive crops are included in crop planning.

Table 4. Land and water allocation at 5 and 25% risk level

Crop	Risk level					
	5%			25%		
	Water application index	Irrigation (cm)	Area (ha)	Water application index	Irrigation (cm)	Area (ha)
Winter wheat	(2)	29.1	46844	(2)	28.3	37919
Wheat	(3)	43.6	59853	(3)	42.4	68778
Mustard	(3)	33.3	2316	(3)	32.0	2316
Berseem fodder	(2)	50.9	6790	(3)	49.7	6790
Monsoon cotton	(3)	48.6	64175	(3)	59.1	100749
Cotton	(3)	72.8	36574	—	—	—
Maize	(3)	35.8	2316	(4)	35.7	2316
Green gram	(2)	25.6	1158	(2)	18.3	1158
Sorghum fodder	(3)	37.5	11580	(2)	17.8	4876
Sorghum fodder	—	—	—	(3)	26.8	6704
Annual net returns (M INR)		1271.5			1304.5	

Case Study of Southwest Haryana

The main hindrance for agricultural development in southwest Haryana is the scarcity of water resources to irrigate farmer's fields. In order to find solutions for optimum water management for this region a regional water management analysis has been carried out using an integrated model for Sirsa Irrigation Circle. (Aggarwal and Roest, 1996)

Description of Sirsa Irrigation Circle

Sirsa Irrigation Circle, with an area of about 0.42 million hectare (ha), represents arid climatic conditions with annual average rainfall varying from 300 to 550 mm, less than 25 rainy days and an annual potential evapo-transpiration from 1500 to 1650 mm. The topography of the area consists of gently sloping terrain with some isolated steep contours in the vicinity of the Ghaggar River. The general direction of the landscape slope is from east to west and towards the Ghaggar river. The different geomorphological units found in Sirsa Irrigation Circle are the recent alluvial plains and aeolian plains with sand and sand dunes. The soil texture varies from loamy sand to sandy loam with some sandy soils occurring in patches.

Canal water supply to Sirsa Irrigation Circle is provided through three canals: Bhakhra Main Line in the north serving about 34,4000 ha; Sukhchain Distributary in the central part serving about 29,500 ha and Fatehbad Distributary in the south serving 18,200 ha. The Ghaggar river is only carrying water during some months in the monsoon season and its water is partly used for irrigation during these months through Ottu feeder. A part of the feeder, infiltrates in the riverbed, resulting in recharging of the groundwater aquifer. Total annual canal water supply was about 5 * $10^9 m^3$. The canal water supply triggered rising water tables in the northwest and southeast where groundwater is poor. Due to deficiencies in the canal water supply, over-exploitation of groundwater in the belt along the Ghaggar river, where groundwater quality is good, caused a decline in the water tables. The maximum annual rise in water table in the northwest and southeast during the period between 1976 and 1991 was over 1 m and the maximum decline in the central part of the area was 0.4 m annually. The scenarios presented here are based on an extensive set of data and gives a more detailed view of the problem for Sirsa district compared to the trends presented on state level.

The groundwater quality on both sides of the Ghaggar river is generally good, resulting in the installation of numerous tube wells in its vicinity during the past several years. Groundwater quality in the western side in Dabwali block is quite poor from varying 7 to 10 dS m^{-1}, restricting its use for irrigation. During the last five years, however, relatively good quality water developed along canals, overlying the saline groundwater, prompting farmers to go for shallow tubewells. General movement of groundwater is from Ghaggar river towards the northwest and southeast. During 1992 water table depths ranged from 1.5 – 25 m in the area with the shallowest groundwater table are found in the Phaggu-Rori area in the east and the deepest in Sikanderpur in the southeast. Serious water logging and salinity problems have emerged in the Phaggu, Desu and Rohan villages of Rori area, leading to the loss of large tracts of agricultural lands.

Major crops in Sirsa Irrigation Circle are wheat, cotton and gram. 17% of potential cultivable land is kept fallow, while about 45% of the remaining area was irrigated in winter and 57% during summer.

Model Calibration and Validation

Study area was subdivided into 46 calculation units for simulation study. The canal water command system was followed in classifying these units. Within the boundaries of calculation units, homogeneity was assumed with respect to soils, cropping pattern, climatic conditions, groundwater salinity and depth of groundwater table depth.

Model calibration on observed historical groundwater levels was performed for the observation period from 1977 to 1988. Calibration was achieved by adjusting number of spatially distributed input parameters such as, storage coefficient, transmissivity and soil physical parameters. After calibration of input parameters for the period from 1977 to 1981, the model was validated for the period from 1982 to 1990. The validation results were satisfactory for the complete study area with predictive value of 75% and higher. In about 52% of study area the predicted values were matching even above 90%.

Description of Integrated Model

Integrated model consists of SIWARE for canal and on –farm water management and SGMP for regional groundwater flow (Smit et al., 1996 and Boonstra et al., 1996). The integrated model comprises of a number of sub-models DESIGN, FRAME, WDUTY and REUSE required for pre-processing of data and computation of water distribution, canal seepage and spatially distributed crop water requirements.

Water Management Analysis

The analysis of water management in Sirsa irrigation circle, using the integrated model, provides observations on: water supply and crop coater requirement and recharge of groundwater.

i) *Water supply and crop water requirement*: The water requirements of irrigated crops were computed by the model that are to be met by canal water supply, rainwater and groundwater exploitation. The water supply from canal and rainfall exceeded the crop demands with about 15% during the first four months from January till April and with about 90% in December. The water supply was deficient by about 30% during the months of May and June and 40-50% during the months of September till November. During the months of July and August the supply covered the demands almost completely. During the period from 1977 to 1990 the average annual shortage of water supply was 210 mm for the water deficiency periods. The average annual excess in water supply was 50 mm with a minimum of 25 and a maximum of 125 mm. The irregular and erratic rainfall caused significant deviation from these average values both in time and space.

ii*) Recharge of groundwater*: Because of the absence of drainage systems, water available through rainfall, groundwater pumpage and canal water in excess of the water holding capacity of soil, percolates to the aquifer system. Recharge causes groundwater table to rise. For a number of reasons the total quantity of water received by Sirsa Irrigation Circle was not fully utilized, and resulted in water table rise. The following recharge components were recognized:

- Excess rainfall on non- agricultural areas
- Seepage losses from canals
- On-farm water losses
- Aquifer recharge by Ghaggar river during the monsoon period.

The seepage losses from canals were about 25% of the total losses and 10% of the canal water supply. On farm water losses were caused by seepage losses from the field irrigation channels, percolation and leaching losses due to rainfall events, especially if they occurred just after field irrigation of crops. Percolation losses during field irrigation were generally not caused by excessive canal water supply, but due to the uneven field water distribution. The border and furrow irrigation methods applied by farmers caused relatively more infiltration at the heads of the fields compared to the tail ends. Also imperfect land leveling and non-ideal sloping fields promoted inhomogeneous water distribution within agricultural fields. The on-farm water losses accounted for about 60% of the total aquifer recharge and 25%of the canal water supply.

Conveyance losses from the canals showed only moderate fluctuations during the period between 1997 and 1990, while the other losses varied from about 175mm ha^{-1} to as much 400 mm ha^{-1}. Defining the overall project efficiency as the ratio of crop evapo-transpiration and total water-supply (including rainfall and groundwater use), the system can be classified as highly efficient with values varying between 68 and 79% for the different years. However, large spatial differences in aquifer recharge occurred in the area, during this period.

The analysis of water management in Sirsa Irrigation Circle revealed that irrigation performance was quite good resulting in a high overall project efficiency ranging from 68% to 79%. The average annual canal water supply was sufficient to meet the water requirements of irrigated crops during winter and early spring, for the winter irrigation intensity of 45%. During the summer and monsoon season the high water requirements for irrigated crops with irrigation intensity of 57% was met through canal irrigation and rainfall for 50 to 60%.

The combined effect of irregular rainfall, canal seepage; water-holding capacity of soils, and irrigation methods used by farmers resulted in percolation losses to the aquifer with a high spatial variability. In about 20% of the area, total annual percolation losses varied from 450 to 625 mm ha^{-1}, in 60% of the area from 150 to 450 mm ha^{-1} and in the remaining 20% from 75 to 150 mm ha^{-1}. The annual canal seepage varied from 85 to 125 mm. The percolation losses together with canal seepage and conveyance losses from the Ghaggar river, caused in major parts of Sirsa Irrigation Circle a groundwater table rise during the period 1977-1990 from 0 to 16 m. In the belt along the Ghaggar river, groundwater tables declined due to significant groundwater abstraction rates. Here the decline varied from 2 to 6 m. The effective porosity in the aquifer system varies from 8-16%, so a change of 1m in water table depth changes the groundwater reservoir with 80 to 160mm.

Alternative Water Management Strategies

Future regional water management strategies for Sirsa Irrigation Circle should solve the problem of rising water tables in the northern and southern part of the area and problem of declining water tables in the central part of the study area. Although, a complete solution cannot be achieved without a drainage outlet to remove the salts imported with the irrigation water, the question remains whether an adapted regional water management could delay the rise of water tables in the endangered zones. This means that alternatives have to be found to reduce the aquifer recharge in the rising water-table areas, increased groundwater use in these areas and/or increased recharge in the areas with falling water tables of reduced groundwater use in these areas.

Increased groundwater use in areas with rising water tables and poor groundwater quality is an issue, which should be solved at the level of on-farm water management. Implementation of such strategies has to be pursued through extension services to farmers in order to convince the profitability to extend their irrigated area using supplemental irrigation and manage the deficient canal water supply.

Out of the four components of aquifer recharge, the regional water manager does not control two. These are the recharge due to rainfall in the non-agricultural areas and the recharge from the Ghaggar river during monsoon. The later takes place in the zone of declining water table and is rather beneficial. Two recharge components are under control of the regional water manager. These are the canal seepage losses and the on-farm water management losses. The canal seepage losses were estimated at about 10% of the canal water supply. Further reduction of these losses of this highly efficient system will be very difficult to achieve.

Two water management strategies addressing the reduction of on-farm water losses to the aquifer were evaluated and discussed as follows. Both strategies were applied for the period between 1971 and 1990, to enable comparison with the historical water table development.

Water Pricing

The analysis of on-farm water management resulted in recommendations to increase the irrigated area using the same amount of canal water. Reduced irrigation water application, as proposed, can be implemented by changing the method of recovering the cost of irrigation water from farmers. Presently, farmers are charged on the basis of irrigated area. Although water charges are quite low, farmers are not encouraged by this system to irrigate more land with the same amount of water.

In the water pricing alternative strategy, it was assumed that payment for water would be based on the amounts of water delivered to farmers, giving farmers freedom to optimize their on-farm water management operations without additional charges. Given the present *Warabandi* water-supply system, which is based on equity, such a change in water pricing methodology does not involve expensive and laborious monitoring of volumes delivered. Simple changes in the basis of pricing from irrigated area from 50% to about 85% was assumed in the simulations by converting the rainfed crops to irrigated crops.

As a result of this strategy, the crop evapo-transpiration increased at the expense of water losses to the aquifer. The annual rise in water table in the utmost northwestern and southeastern part of Sirsa district reduced by about 15%. By adopting this strategy water logging problems cannot be avoided, but can be postponed by 5 to 10 years. At the same time total crop production in the area appeared to increase as well. However, through this strategy, declining water table in the central part of the area was not arrested.

Water Supply According to Demand

Adjusting the temporal and spatial canal water supply to the actual crop water requirements of the irrigated crops can obtain additional water use efficiency improvements. Presently, canal supply exceeds requirement by about 55 mm during the winter period and the late summer shortage in supply is about 210 mm. The present canal water distribution is based on cultivable area rather than on water requirements of the irrigated cropping pattern. This could be improved by discarding the *Warabandi* system and by distributing canal water based on the spatially distributed crop water requirements. During the monsoon period, irrigation water requirements depend to a large extent on rainfall. Solutions for technical and managerial provisions to adjust canal water supply to the erratic and spatially distributed rainfall conditions were considered beyond the scope of study. Although application of regional models as predictive tools, can play prominent role in future water management accounting for rainfall, at this stage, long-term average rainfall has been assumed as input for matching the water distribution with the spatial and temporal distributed water requirements.

The effects of this regional water management strategy were expressed in the number of years elapsed until water logging occurred. In the reference situation with unchanged water management, in about 10% of the Sirsa Circle, water logging problems will occur within a time period of 15 to 45 years. With water distribution matching the temporally and spatially distributed water requirements, these percentages are considerably reduced. In about 5% of the area water logging is expected within 5 years, in about 15% of the area within 5 to 15 years and in about 25% water logging problems will occur within a time period of 15 to 45 years. An additional benefit from this alternative is that in the central part of Sirsa district with declining water table, a status quo or a reversed situation was achieved.

Evaluation of Alternatives

Compared to the present canal water management system in Sirsa Irrigation Circle, both, alternative strategies have the advantage that rising water tables were delayed in the saline groundwater areas in the north and south of Sirsa district. Water distribution according to demand was slightly more effective in these areas. In the central part of Sirsa district water distribution according to demand led to slightly rising water tables. This could easily be corrected by reducing canal water supply to these areas or by compensating the increased recharge with more groundwater use.

The strategy of changing water pricing has the obvious advantage that no investments are required and operation of the canal system can be maintained at the present mode. The strategy with distribution according to demand requires a differentiated allocation and distribution of canal water and the present system of distribution based on equity has to be abandoned. For the strategy with distribution according to demand a number of practical constraints have to be solved: water scheduling and control requires more labour and additional investments to adapt water control structures. Such a system will be more susceptible to sabotage and bribery by influential farmers trying to receive more canal water. Also social and political constraints must be solved before implementing such a strategy. Farmers in the advantageous situation with access to good quality groundwater will receive more canal water than their colleagues in the poor quality groundwater zones.

Policy Implications

The lessons drawn from three case studies –Southwest Punjab and Srihand Canal Tract in Punjab and Sirsa Irrigation Canal in southwest Haryana provide evidence for policy issues pertaining to management of groundwater. The policy implications that can be drawn are:

Groundwater Legislation

There is need to enact proper groundwater legislation to prevent indiscriminate exploitation of groundwater resource. In addition, inheritance of property law also needs to be modified to prevent progressive fragmentation of land holdings. The task of water distribution becomes very simple and easy for a big size holding from an outlet in comparison to different sizes of holdings scattered all over the command area.

State Water Authority

India's National Water Policy (Ministry of Water Resources, 2002) clearly recognizes that exploitation of groundwater resources should be regulated so that it does not exceed recharging possibilities, and also ensures social equity. The detrimental environmental consequences of over-exploitation of groundwater need to be effectively prevented by the central and state governments. Water being the state subject, the State Water Authority should be set up with an aim to regulate and control groundwater development and management on sustainable basis.

Agricultural Power Supply and Pricing Structure

The use of flat rate for electricity, combined with unreliable electricity supply provides no incentives for efficient use of groundwater. The subsidized electricity tariff also results in heavy financial losses to State Electricity Boards. Thus there is an urgent need to revamp agricultural power supply and tariff structure. Specific policy issues aiming at sustainable use of groundwater will need supporting initiatives which ensure fair prices for alternate crops to growers through state mediated system.

Restructuring Subsidies

There is a need to restructure subsidies to encourage farmers to adopt efficient irrigation methods and improve water management with a view to improve groundwater use efficiency.

Stakeholder Participation

Participation of farmers, NGOs and scientists in defining and pursuing the strategies for sustainable resource use should be encouraged.

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Application of Hydraulic and Economic Optimization for Planning Conjunctive Use of Surface and Saline Ground Water: A Case Study

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Abstract

Conjunctive use of water from different sources is considered to be a valuable tool to overcome the constraint of the surface and groundwater systems, if operated independently. The conjunctive use planning requires establishment of firm water supplies and their distribution, effect of water development and use on groundwater behaviour, allocation of water to different users based on economic returns and tolerance to salinity,and effect of saline water use on surface and groundwater salinities. Decisions regarding the development and allocation of water are complicated processes and are best attempted through modeling. This paper deals with formulation and application of groundwater hydraulic optimization and allocation models for planning the development and use of surface and groundwater in Lower Ghaggar Basin of Haryana,India.

The problem of conjunctive water development and utilization planning has been dealt as a two-stage process. The first stage, deals with determination of optimal groundwater development, while the second stage, deals with water allocation to crops in a conjunctive use milieu. For hydraulic optimization, a steady state flow optimization model has been formulated to develop optimal groundwater pumping strategies. The model predicts the optimal pumping volumes and the resulting groundwater potentiometric surfaces. In association with a groundwater simulation model, it also makes possible to forecast the time frame in which groundwater table in different sub areas in a region, would attain steady state condition. The special features of the model are the inclusion of functions for stream-aquifer interaction and direct evaporation from the ground watertable. For water allocation and economic optimization, a non-linear conjunctive water use-planning model is formulated. The model maximizes net benefits from water use of varying salinities through allocations to different crops and determines the optimal groundwater pumping for irrigation and drainage water disposal.

Results of the application of the hydraulic optimization model show that there is considerable scope for augmenting the groundwater supply in areas adjoining the River Ghaggar by increasing stream-aquifer interaction. The present stream aquifer interaction in river cells is of the order of 16 m^3s^{-1}*, which can be increased to 26* m^3s^{-1} *with optimal pumping. The optimal potentiometric surfaces fall in the range of 184 to 214 m above MSL giving a water table depth of 4 to 22 m, thus ensuring against waterlogging and salinity development.*

A non-linear conjunctive water use optimization model decides the water allocation to different crops and mapping of the resultant groundwater quality scenarios. A GAMS version of the model is prepared for analysis with GAMS/ MINOS software. The allocation essentially centres on crop-water-salinity production functions, which are non-linear in nature. The required production functions have been developed with basic data on crop-water-production and applied water-salinity-yield functions. The two functions for which the experimental data were available from different sources are synthesized into a single water-quality-quantity production function. The required costs and benefits estimates for different activities were developed using standard techniques of estimating and costing. The estimates of groundwater in different quality zones are based on water quality information from shallow tubewells, which was subjected to analysis by statistical software called GEOEAS.

It appears from the results of economic optimization that cash crops such as cotton and mustard, which are otherwise, also salt tolerant, will find favour with increased saline water use, if risk associated with pest and disease is minimized. Increase in cost of water is not likely to make any difference in water allocation due to large differences between return from water use and the present cost of irrigation water. Conjunctive use of saline groundwater with canal water on sustained basis will require disposal of some part of saline water through evaporation ponds and regional drains. Volume of groundwater to be disposed is governed by quantity and quality of canal water supply and the quality of groundwater. This minimum quantity of disposable water in the lower Ghaggar Basin is 14 percent of the annual recharge.

Introduction

The survival of mankind depends upon its ability to produce enough food and provide enough water for public health and industrial purposes. As the competition for water grows, the need to use the available resource efficiently without impairing its quality increases. This can be achieved by proper planning and management of water resources. For surface water, the stream flows with high temporal and spatial variability, are to be converted into a set of comparatively regular flows. For groundwater, the pumping rates are to be adjusted to suit the aquifer properties and the sustainable recharge. Optimal development of water resource is generally the outcome of the conjunctive use of water from various sources (Hall, 1986). Conjunctive use of water resources can be defined as the management of multiple water resources in a coordinated operation such that the water yield of the system over a period of time exceeds the sum of water yields of the individual components of the system resulting from uncoordinated operation. Normally conjunctive use is planned and practiced with the objectives of mitigating the effect of shortages in canal water supplies, increasing the dependability of the existing water supplies, alleviating the problem of high water table and salinity, facilitating the use of high salinity groundwater and mitigating the damages due to drought (Abrol et al., 1988).

In the canal irrigated area, introduction of huge quantities of water from outside areas, results in disturbance of existing hydrologic equilibrium of the groundwater basin. Increased groundwater accessions induce positive net recharge, forcing a rise in water table very close to the surface and creating significant waterlogging and salinity. In areas, where groundwater quality is good and aquifer formations favorable, increased recharge adds to the water resources of the area in a dependable manner. This is because such water can be developed and used according to crop requirements. However, in many places, irrigated areas are underlain by aquifers of poor quality and in normal course; there is very little groundwater development in such areas. In the absence of commensurate ground water withdrawal, rise in water table beyond permissible limit is inevitable. Such a situation exists in a major part of the southwestern part of Haryana, Punjab and north and eastern parts of Rajasthan. States of Gujarat, Maharashtra, Karnataka and Tamil Nadu also face similar situations.

Under the given surface water supply conditions, the development and use of water resources in the saline ground water basin involves four distinct processes. The first process, is concerned with planning the development of resources. Mathematical models, that can simulate and predict the system response to the management and hydrologic simulation, are often used for planning the development. Outputs from simulation model do not answer the whole range of questions and a different set of the models called optimization models are required (Lefkoff and Gorelick, 1990). The second process, is concerned with simulating the effect of saline water use on crop production. This is, essentially an agronomic component and has to do with establishing crop-water-salinity production function. The response of crops and stages of growth to water and salinity stress differs. The effect is also amenable to change with water application technologies and cultural practices (Zeng et al., 2001). The third process, deals with hydrologic system in saturated and unsaturated zones. Development and utilization of water resources disturbs the hydrologic equilibrium. The system remains in transient stage till the new equilibrium is reached. The direction of change may be both positive (beneficial to the environment) and negative (harmful to the environment), but extremes in either direction are unfavorable to the environment. In physical terms, the process includes changes in the hydro-salinity regimes of the ground water basin. The fourth and final process is economic in nature and deals with profitability of investments.

A number of conjunctive use planning models have been developed to determine pumping rates for a sustainable potentiometric surface (Tyagi et al., 1995), allocation of water to areas under different crops and optimal hydro-salinity regimes in a basin (Tyagi, 1987). The economic aspects of water allocations have received greater attention and both linear (Khepar and Chaturvedi, 1982; Tyagi et al., 1993) and dynamic programming models (Knapp and Wichelns, 1990) have been used in such studies. Groundwater simulations have also received greater attention, and analytical as well as numerical approaches have found use (Helweg and Labadie, 1976; Lefkoff and Gorelick, 1990), but the models that develop a quantitative understanding of economic, agronomic and hydrologic processes that occur in a saline irrigated system have been rather limited.

This paper deals with formulation and application of ground water hydraulic and economic optimization models for planning the development and use of surface and ground waters in Lower Ghaggar Basin (LGB) of Haryana,India. In this paper the problem of conjunctive water development and use planning has been addressed as a three-stage process. The first stage deals with the determination of optimal ground water pumping. The second stage is concerned with the development of crop-water-salinity production function. The third stage, relates to hydro-economic optimization of water use and is performed to maximize benefits from conjunctive use in a sustained manner. Measures that would facilitate development of groundwater on extensive scale in the poor water quality zones are briefly discussed.

Study Area

The study area extends over 51,300 ha in the Ghaggar River Basin in Sirsa and Hisar districts of Haryana in India (Figure. 1). The area has the possibility of exploiting groundwater through shallow tubewells. Analysis of water samples collected from observation wells of shallow depths from various parts of the study area indicate that maximum value of electrical conductivity (EC) is 16.8 dS/m and the minimum 1.3 dS/m. The sodium adsorption ratio varies from 0.1 to 17.1.

In few locations, the waters are sodic in nature with (RSC) of more than 2.5 me/l. From consideration of salinity (EC), fresh water aquifers occupy 12% area (EC < 2 dS/m), marginal water (EC 2-6 dS/m) 53% and saline water (EC >6 dS/m) 47%. 73% of the groundwater has RSC of less than 0.2 me/l. The sodium adsorption ratio (SAR) varies from 0.2 to 1.7, and 86% of the water have SAR less than 10. There is limited canal water supply (Bhakra Canal System) to supplement the precipitation and groundwater. Due to the absence of adequate groundwater development and continuous utilization of canal water supplies, the groundwater levels and salinity are increasing. At the same time the total water supply is not sufficient to achieve high irrigation intensity.

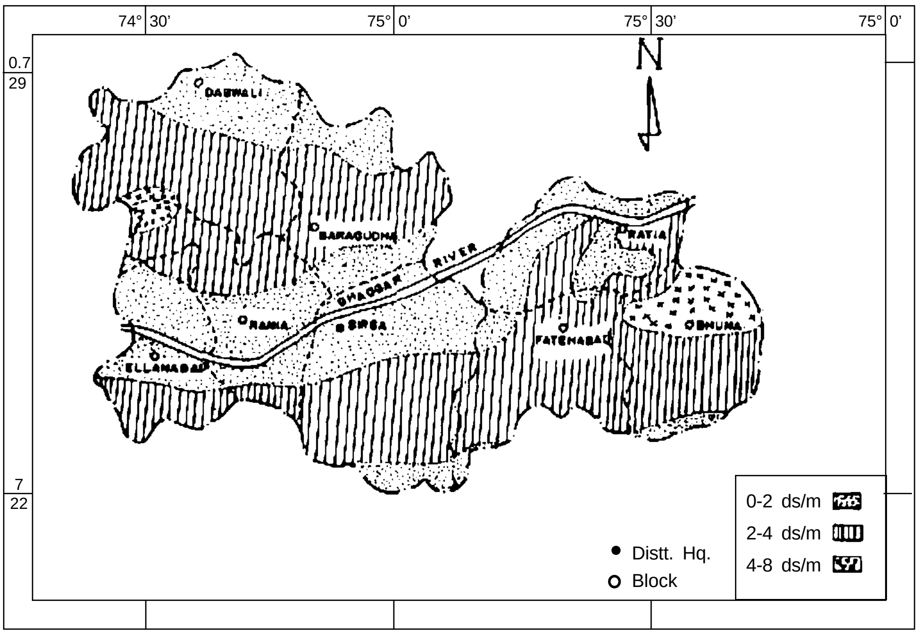

Figure 1. Location and ground water quality in lower Ghaggar basin

There is also a need to dispose off part of the pumped ground water to maintain the salt balance in the groundwater system, thereby preventing groundwater quality deterioration. The irrigated system lies in land locked area with little scope for disposal of saline water outside the system. At present evaporation ponds are the only possibility to dispose extra saline water for maintaining a favourable salt balance in the aquifers. There may be some adverse environmental impacts but considering the socio-economic conditions in the area, the benefits far exceed the possible environmental damage.

Hydraulic Optimization and Water Allocation Models

A schematic diagram of the linkages in the optimization and water allocation models is shown in Figure 2. A steady state optimization model to evolve groundwater development strategies and a water allocation and economic optimization model are formulated to aid in development of management strategies.

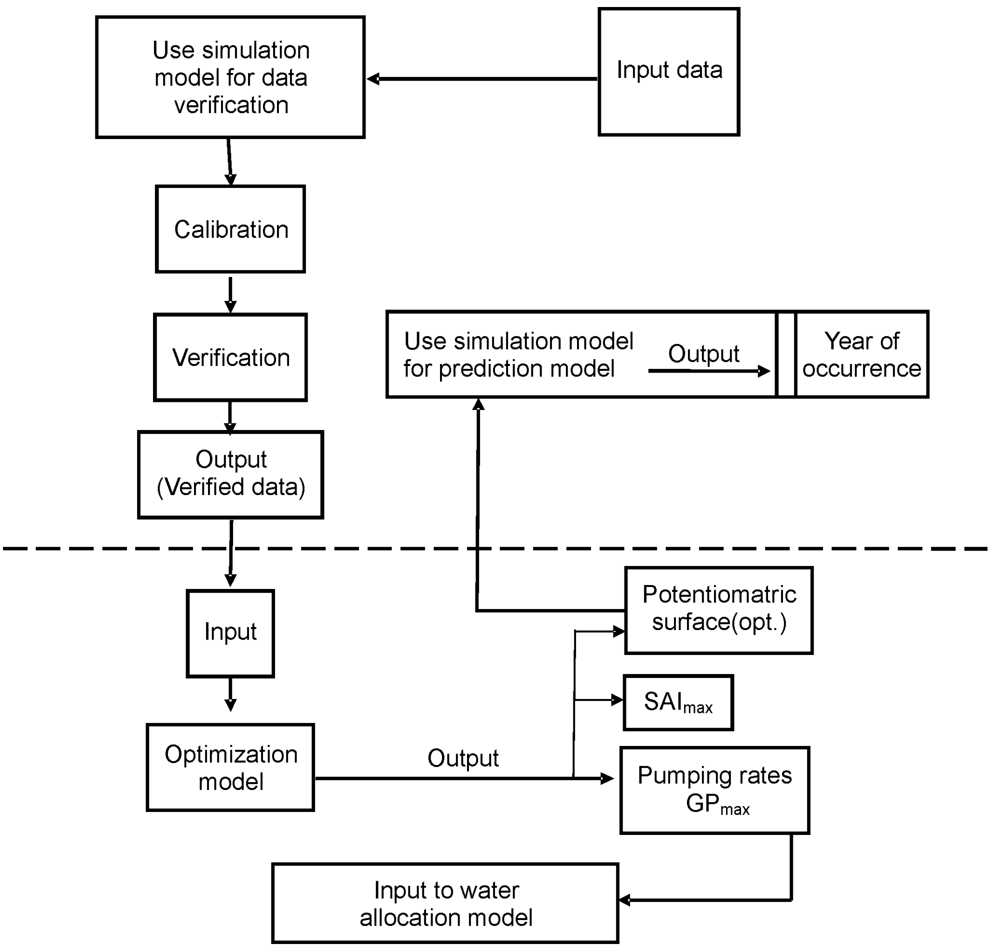

Figure 2. Linkage between simulation and optimization model

Steady-state Flow Optimization Model

The model consists of an objective function and a number of constraints. The objective function gives the maximum sustainable pumping yield for the entire area under well-defined constraints and bounds. The total sustainable pumping is the sum of individual sustainable pumping of each sub area, which has its local bounds and limits.

The size, number and distribution of the nodal areas and the location of the natural and arbitrary boundaries of the study area have been decided on the basis of transmissivity, storativity and groundwater levels. Keeping in view the constraints of quality and availability of basic data, the area was discretized into 30 nodes, of which 15 were internal nodes and the remaining 15 are external nodes (Figure 3). The 15 internal nodes are variable head cells, where the study is being made to evaluate the pumping strategies. The 15 external nodes are primarily required to construct the network near the boundaries.

Ideal boundary conditions described do not exist there. A groundwater simulation study had been conducted in part of the LGB with a view to have preliminary estimation of the water level fluctuations and behavior (HSMITC, 1983). The existing nodal network has been superimposed on the nodal network used in that study and the boundary conditions have been interpolated. The western boundary of the study area, where a condition of low recharge and low pumping exists and water levels do not vary throughout the year, is considered as zero flow boundary. On the other three sides, the boundary is assumed to be flow controlled.

The steady-state excitation rates are those values of pumping and recharge which, when applied to the system, continuously maintain constant potentiometric surface elevations. For a given set of potentiometric surface elevations, there exists a corresponding set of steady-state pumping values*.

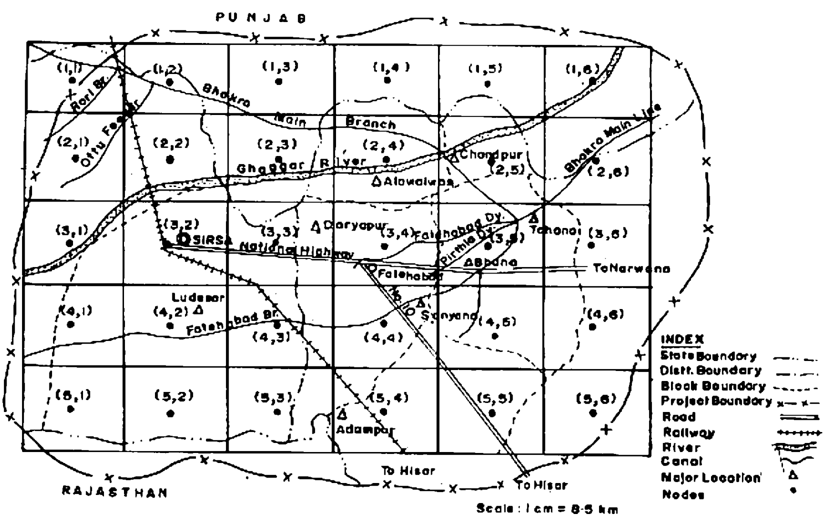

Figure 3. Study area discretized into finite difference cells

*See Tyagi, et al. 1995 for the Mathematical form of model.

The Water Allocation and Economic Optimization Models

The groundwater optimization model described in previous section can be used to determine the optimal levels of groundwater development. Formulation of a canal and groundwater conjunctive use model is attempted to assist in planning strategies for water allocation to crop activities. Disposal of saline ground water to maintain salt and water balance in the crop root zone as well as in aquifer, is an integral part of the model. The problem is treated as non-linear optimization, and a conjunctive use management model is developed.

The model allocates water to a number of crops according to their sensitivity to saline water to maximize net returns. The income is generated from disposal of crop produce while the cost is incurred in purchase of canal and tubewell water. The non-water production inputs are treated as fixed costs. To keep the groundwater salinity at original level, part of the groundwater pumped is disposed through evaporation ponds and has a cost. The detailed mathematical formulation can be found in Srinivasulu et al. (1997).

Crop-Water-Salinity Production Function

Crop-water-salinity production functions are essentially the mathematical relationships between yield of crop and the amount of applied water and its salinity. The model requires empirical relations that can be used to study the effect of water quality, quantity and their interaction. The approach used is based on combining the crop-water-quantity and the crop-water salinity production functions, first proposed by Letey et al. (1985). The crop-water-salinity functions for important crops used in this model were developed by Srinivaslu and Tyagi (2001) and are given in Table 1.

Table 1. Crop-water-salinity production functions

	$RY = a+b(AW/Ep)+c(AW/Ep)^2+d(S_j)+e(S_j)^2+f(AW/Ep)(Sj)$					
Crop	a	b	c	d	e	f
Wheat	-0.1668	1.4465	-0.2947	-0.0071	0.0005	-0.0302
Mustard	-0.2718	1.6733	-0.4662	-0.0065	0.0002	-0.0282
Berseem	-0.1150	1.2603	-0.1027	-0.0189	0.0024	-0.0958
Cotton	-0.2431	2.5401	-1.0751	-0.0087	0.0003	-0.0345
Pearl millet	-0.8671	2.9815	-1.0102	-0.0066	-0.0012	-0.0534
Maize	-0.4692	2.5843	-0.9030	-0.0142	0.0018	-0.0661

Source: Srinivasulu & Tyagi, 2001

Optimal Ground Water Pumping and Water Allocation Scenarios

The groundwater hydraulic optimization and the conjunctive use management models mentioned in the preceding sections were applied to develop optimal plans for groundwater development and its use in conjunction with canals for the LGB. In case of groundwater optimization model the data were first prepared for the groundwater simulation model set for the same area. Tyson and Weber model

(1964) as modified by Goodwill (1989) was used. The data screened in the process of calibration of the simulation model were subsequently used in the optimization model. The procedure employed is explained in Figure 2. Possibilities of augmenting groundwater supplies have been explored through increased stream-aquifer interaction. Issues concerning sustainability of saline water use have also been explored.

Hydraulic Optimization

The model was run for steady state condition using Linear Programming (LP) algorithm written in GAMS. The output from the model include: optimum pumping rates, resulting potentiometric surfaces and stream-aquifer interaction.

Pumping Rates

The pumping rates for different cells are given in Table 2. It is seen that there is wide variation in optimal discharge among different cells. The values range from 0.25 cumecs to 8.48 cumecs. The pumpable quantities of groundwater depend largely on recharge opportunity and the type of aquifer. Areas falling along the course of rivers and perennial canals have higher opportunity for recharge as compared to cells or sub areas located away from the river and perennial canals. For example, the river cells 2,2; 2,3; 2,4; 2,5 and 3,1 have pumping rates 4 to 20 times of non-stream cells 3,2; 3,3 and 4,1.

Table 2. Values of model outputs

Internal nodes	Draw down (m)	Saturated thickness (m)	Optimal head (m)	Optimal pumping (cumecs)
2,1	1.26	106.66	195.54	2.59
2,2	-8.00	108.53	200.61	7.93
2,3	1.33	102.32	202.62	8.48
2,4	0.67	93.55	210.58	8.10
2,5	1.00	118.76	213.97	2.39
3,1	8.00	112.17	176.56	2.42
3,2	-3.16	100.82	184.32	2.02
3,3	4.27	94.11	195.43	0.85
3,4	7.00	99.64	195.27	1.32
3,5	6.00	109.85	200.53	1.65
4,1	-2.80	135.21	185.81	1.90
4,2	-3.29	127.35	201.25	0.25
4,3	3.77	112.89	192.94	1.50
4,4	1.56	107.72	193.91	1.34
4,5	-0.35	118.19	197.78	1.39

The optimal pumping rates were compared with existing (1985) pumping rates. It was observed that in the river as well as in the non-river cells, the existing pumping rates are much lower than optimal pumping rates. As expected, the river cells have higher current pumping rates. The magnitude of the difference between optimal and current pumping rate varies from less than 0.5 cumecs to more than 8 cumecs. This difference in potential and current pumping rates is responsible for rise in water table.

Potentiometric Surface

Potentiometric surfaces have several implications for ground water management. If the surfaces will be high, it will lead to waterlogging resulting in direct evapotranspiration from soil surface and cause salinity. If the potentiometric surfaces are very low, the pumping cost may be high for economic exploitation of groundwater. Further, in areas where groundwater quality problem occurs, the quality deteriorates with depth (in most cases). Therefore, decisions about desired potentiometric surfaces have to be chosen with care. The existing potentiometric surfaces have values between 185 m to 216 m above mean sea level (MSL) and the corresponding depth to water table is within 4 to 17 m (Figure 4). In areas where the average depth to water table is within 4 to 5 m, such as those represented by cell 2,1; 2,3, part of the area suffers from high water table and salinity. The results from groundwater simulation model (Tyagi et al., 1996) indicated that the water table had a rising trend with rates varying 0.22 to 0.60 m/year. It means, though at present the water table is below the critical levels, in the absence of groundwater development, it may become critical at some future date.

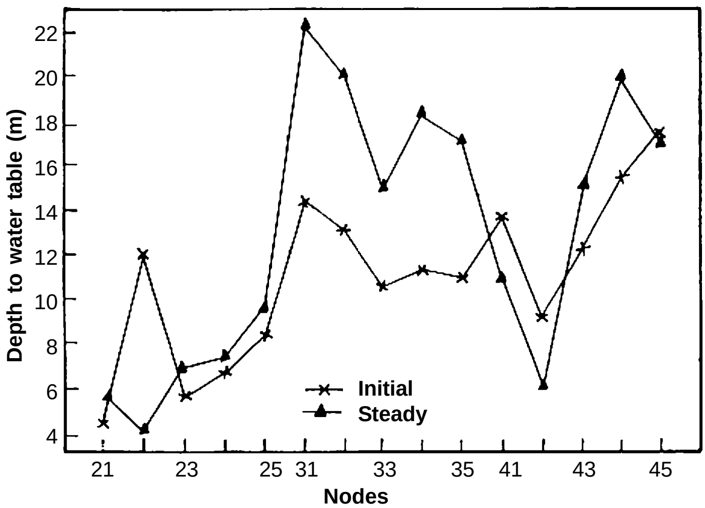

Figure 4. Depth to water table in maximization scheme

The optimal potentiometric surfaces, that have been obtained with the application of model fall in the range of 184 to 214 m above MSL giving a depth of water table 4 to 22 m. It is observed from the depth to water table graph (Figure 4) that under the steady-state situation the water table would fall below the existing level by 2 to 7 m, except in case of cell 2,2; 3,2; 4,1; 4,2 and 4,5 where the water table would come up. The maximum difference in initial and steady-state water table is 8 m in cell-3,1 whereas the minimum difference is 1 m in case of cell-2,4. The cells-2,2; 2,3; 2,4 and 2,5 are river cells with high pumping rates. In spite of higher pumping rates the draw down are low because of continuous recharge from the river and perennial canals. However, in case of cell 3,1, which is also river cell, the draw down is maximum (8 m) though the steady-state pumping rate for the cell is only one-third of the other river cells such as cell- 2,2; 2,3 and 2,4. This cell lies in area where there is an abrupt fall in the riverbed elevation. Since the surface water body in the form of left and right Ghaggar canals are at higher elevation, the water table around this area is higher than river bed and contributes to sub-surface flow into the river. The saturated thickness of the aquifer in the whole region is in the range of 93.50 m to 135.20 m. In the model, a constraint has been put on the maximum draw down (lowering of water table from initial level), which would not allow the water table to fall more than 50 percent of saturated thickness of the aquifer.

Stream-Aquifer Interaction

Stream-aquifer interaction (SAI), which may involve flow from aquifer to stream or vice-versa is an integral part of the model. As has been indicated earlier, the possibility of SAI exists in areas, having large or perennial flowing surface water bodies such as river, canal and ponds. The magnitude of SAI is determined by the hydraulic head difference between water bodies and aquifer, and the conductance of the transmitting medium. On the basis of the available water table elevations and the elevation of surface water body, and the conductance, the current SAI i.e. flow to and from the water body were determined. As the pumping increases the head differential between surface water bodies and groundwater table level also increases, facilitating higher SAI. In case of maximized scheme, the total SAI is 26.08 cumecs as compared to current interaction of 20.81 cumecs (Table 3). In case of minimized pumping scheme, which maintains water table 3 m in the entire area, the SAI reduces to 21.92 cumecs. The increase of about 25% in SAI at maximized pumping rates indicates the feasibility of generating more water resources from river flow, which at present goes waste and creates waterlogging problem at tail end of the Ghaggar depressions in Rajasthan.

Pumping Scheme

Meeting the maximized pumping rate would require a large number of tubewell units. In this area, shallow tubewells and pump sets are frequently used. At present, the number of tubewell units is few and they are sparsely spaced. In order to obtain the optimized potentiometric surfaces, the differences between current pumping units and the optimally required pumping units must be reduced. The average pumping rates of shallow tubewells vary from 4 lps to 8 lps (HSMITC, 1983). The operation time of shallow tubewells in the area is 10 hours a day for about 100 days in a year (HSMITC, 1984). In case of maximized pumping scheme the number of pumping units is around 8 times of units existing in 1985. Recent estimates show that the number of pumping units has more than doubled: from 37,262 in 1985 to 82,682. The pumping units have to be increased in all the cells, though larger increase is required in river or canal cells. It should be understood that for all tubewell discharges (4-8 lps), the number of tubewells per unit area is

Table 3. Maximized interflow, boundary flow and current interflow in each river cell and boundary cell under maximized steady-state scheme

Nodes (Variable head)	Maximum interflow (cumecs)	Nodes (boundary)	Boundary flow (cumecs)	Current interflow* (cumecs) (1985 Data)
2,1	-1.73	1,1	-0.095	-1.73
2,2	-6.97	1,2	-0.095	-4.77
2,3	-6.97	1,3	-0.095	-4.75
2,4	-7.08	1,4	-0.095	-5.26
2,5	-1.38	1,5	-0.015	-1.38
3,1	-0.45	1,6	-	-0.40
3,2	-	2,6	-0.070	-
3,3	-	3,6	-0.080	-
3,4	-	4,6	-0.090	-
3,5	-0.11	5,1	-0.090	-0.12
4,1	-0.45	5,2	-0.140	-0.45
4,2	-0.30	5,3	-0.090	-0.31
4,3	-0.34	5,4	-0.090	-0.34
4,4	-0.15	5,5	-0.070	-0.15
4,5	-0.17	5,6	-	-0.17
Total	26.08		1.145	20.81

* 1985

not the same. One would require more number of tubewells to extract a given volume of water per year with low discharge tubewells. The average density for maximized pumping tubewell scheme works out to be 12.5/100 ha.

Conjunctive Water Use Management Plan

The results from application of water allocation model are discussed in terms of cropping patterns, groundwater disposal policies, total benefits and benefits per unit area/applied water.

Cropping Pattern

Two crop seasons (*kharif* and *rabi*) with three irrigated crops in each season were considered. There could be crop areas under rain fed farming, but these were not part of the present decision process. Of the total irrigated area of 15,391 ha in *kharif*, 80.1% is occupied by cotton and 11.3% by pearl millet. The remaining 8.6% area is allocated to maize. The irrigation intensity during *kharif* season works out to be 36.6%, and the value of irrigation intensity during *rabi* is 47.7%. Thus, the annual irrigation intensity is 84.3%. The area under irrigated farming during *rabi* is higher by 30% as compared to *kharif*. This may be due to higher profitability of the *rabi* season crops. The total benefit resulting from optimal water allocation is Rs. 165.92 million. The benefit per unit of water use is Rs. 108.6/ha-cm during *kharif* and Rs. 120.8/ha-cm during *rabi.*

Water Allocation

Of the total water supply from canal and groundwater, 588,000 ha-cm is used during *kharif* and 959,345 ha-cm during *rabi*. During *kharif*, cotton is allocated 83.1% of the total water and the remaining is shared almost equally between pearl millet and maize. During *rabi*, major share of saline groundwater goes to mustard (50.3%), followed by wheat (41.4%) and berseem (8.2%). In the existing allocation, wheat receives more than 60% of water supply.

Ground Water Disposal

The sustainability of irrigated agriculture depends on keeping groundwater table and its quality within the permissible range. Whereas it is possible to keep water table within acceptable limits by groundwater development and its use within the basin, it is not so with ground water quality. The groundwater quality can be maintained at the existing level only if salt input and output are kept fully balanced. Along with water allocation to crops, the model also computes the ground water to be pumped and the volume of groundwater to be disposed in different quality zones. As per the constraints imposed in the model, 625,345 ha-cm ground water is pumped annually. This is, 15% more than the average annual recharge. Of the total ground water pumped, 86,000 ha-cm is disposed through evaporation ponds. This is about 13.8% of the total ground water pumped.

All the water of 0-4 dS/m range is used for irrigation and the waters of 4-6 dS/m and >6 dS/m range are disposed through evaporation ponds. The fraction of the groundwater disposed through the evaporation ponds increases with increase in ground water salinity. This has got two implications: (i) better water quality is more beneficial for irrigation, and (ii) disposal of higher salinity water through evaporation permits maintaining salt balance in the basin with relatively lower disposal volumes. It should, however be understood that in this analysis the entire ground water basin has been treated as one. If it is disaggregated, then one will have to determine groundwater evacuation and disposal from individual cell.

Table 4. Net benefit per unit water use and water disposal as affected by ground water salinity (SG)

Item	At existing	2 SG_o	3 SG_o	4 SG_o Salinity (SG_o)
Net benefit (10^6 Rs.)	179.94	166.75	163.86	159.27
Water used (10^3 ha-cm)	1547.35	1575.42	1591.58	1602.05
Net benefit per unit water use (Rs./ha-cm)	116.16	111.76	107.18	102.55
Ground water disposal (10^3 ha-cm)	58856.00	39649.00	28589.00	21441.00

Sustainability of Saline Ground Water Use

It is possible to maintain water table at the prescribed level without groundwater disposal by adjusting groundwater pumping. However, it is not a practice that can be sustained on long-term basis. In the absence of disposal, the salt load in the groundwater reservoir will continue to increase and after sometime the negative effects of rise in groundwater salinity will start appearing in the form of reduced yields and lower net benefits. In order to evaluate the level of groundwater salinity, at which the cost of disposal and benefits from increased availability of ground water without disposal will balance yield and income reductions, the model was run at various groundwater salinity levels. The resulting benefits from water use without disposal were compared with benefits occurring with ground water disposal at various salinity levels (Figure 5).

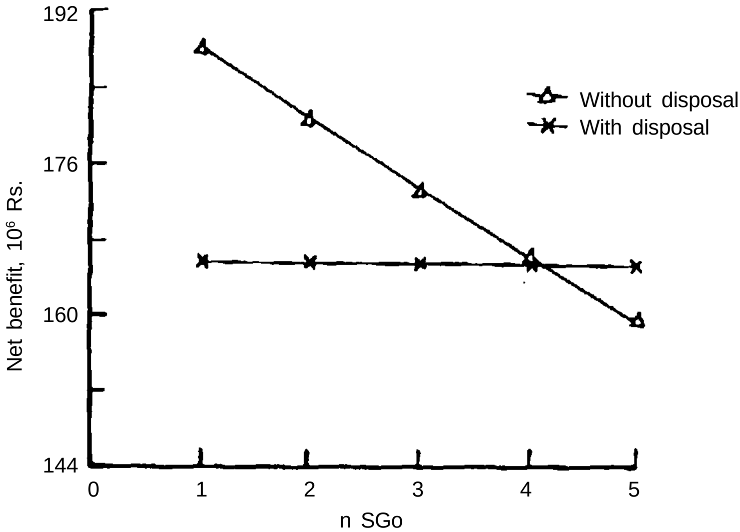

Figure 5. Net benefit with and without disposal at various levels of ground water salinity (SG)

It may be seen that the benefits from optimization scheme without disposal were higher than benefits with disposal upto a salinity level nearly 4.1 times that of original salinity. It has got the following implications from the viewpoint of operation and management of saline ground water in conjunction with canal water:

(1) Investment on disposal in the form of evaporation ponds can be deferred till such a time, that the yield losses from increased groundwater salinity nearly balance the cost of disposal. The duration for which, investment can be deferred will depend upon the original salinity of the ground water, rainfall amount, and its distribution, canal water quality and quantity.
(2) The level of investment in groundwater disposal through evaporation pond should be less than or equal to the annual reduction in net benefits.
(3) Whereas lowering of water table and keeping it below critical levels is a necessary condition for sustainable conjunctive use of fresh and saline waters, it is not a sufficient condition. The sufficiency is provided by salt disposal only.

Concluding Remarks

The application of groundwater simulation and optimization models in this paper is based on data, which was available at a large irregular grids.The availability of hydro- geologic data on micro-scale is desirable not only for better prediction but also for development of saline ground water aquifers, which exhibit large spatial variability. The development and use of ground water in the study area, part of which is saline in nature, in conjunction with canal water is providing opportunity of increasing production and minimizing risk of water logging. There has been more than 230% increase in groundwater development since the study was first undertaken in the late eighties, but the full advantage that would occur from inducing recharge in Ghaggar River bed, has not been taken. The development of higher salinity water continues to be low due to several technological and economic constraints. Efforts would be needed both at farmers' level, as well as, at government level to realize the potential gains of conjunctive water management. Maybe, introduction of brackish aquaculture could promote higher salinity ground water development.

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Management Options and Policy Guidelines for Use of Poor Quality Groundwater in Agriculture

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Abstract

The anticipated shortage of fresh water supply to agriculture sector in the 21st century is likely to enhance globally the utilization of relatively poor quality water for irrigation. The poor quality ground waters occur extensively (32-84%) in the arid and semi-arid parts of India and their indiscriminate use poses serious threat to the sustainability of natural resources and environment. Water quality studies over past few decades have enabled development of technological options to cope up with the problems of saline and sodic water use. Possibilities have now emerged to safely use water otherwise designated unfit. These options primarily consist of: i) selection of crops, cropping patterns and crop varieties that produce satisfactory yields under the existing or predicted conditions of salinity and sodicity ii) appropriate irrigation scheduling and conjunctive use options with canal water; rain water management and leaching strategies to maintain a high level of soil moisture, and low level of salts and exchangeable sodium in the rhizosphere, and iii) use of land management practices to increase the uniformity of water distribution, infiltration, and salt leaching besides the optimal use of chemical amendments including time and mode of their application with judicious use of organic materials and chemical fertilizers. Some of the policy guidelines such as establishing water quality monitoring networks, modifications in canal water delivery schedules, groundwater pumping pricing, subsidies on amendments and micro-irrigation systems, promoting conjunctive use and ground water recharging and training need for farmers and extension workers are also highlighted.

Introduction

The availability of fresh water supplies to agriculture sector in future is likely to reduce world over particularly in the Asian countries due to population pressure, improved living standards and inter-sector competition for water. The estimate for India shows this reduction to be 10 to 12% by 2025.

In the back drop of this grim water scenario, the agriculture sector would be left with no other alternative than to use poor quality water sources to meet the irrigation requirements. The ground water surveys in India indicate that poor quality water being utilized in different states range between 32 to 84% of total ground water development. Many more areas with good quality aquifers are endangered with contamination as a consequence of excessive withdrawl of ground water. The ground water of arid region are largely saline and of semi-arid region are sodic in nature.

Indiscriminate use of poor quality water for irrigating agricultural crops deteriorates the productivity of soils through salinity, sodicity and toxic effects. In addition to reduced productivity, the use of poor quality water deteriorates the quality of produce and also limits the choice of cultivable crops. Nevertheless, concerted efforts at different research centers located in different agro climatic zones of the country have yielded valuable concepts and viable technologies for the sustainable irrigation with poor quality water (Minhas, 1996). Possibilities have emerged to safely use water otherwise designated unfit if the characteristics of water, soil and intended crops are known. However, appropriate selection of crops, improved water management and maintenance of soil structure permeability are necessary for sustaining irrigation with these waters. In this paper we have outlined various technological and policy options available for alleviating hazards of salt-affected water and maximizing productivity form their sustained use.

Classification of Irrigation Water

Irrigation waters are mainly classified on the basis of electrical conductivity (EC), sodium adsorption ration (SAR) and residual sodium carbonate (RSC). However, from management point of view, ground water utilized in different agro-ecological regions can be broadly grouped into three classes: good(A), saline(B) and alkali/sodic(C). Depending on the degree of restriction, each of the two poor quality water classes has been further grouped into three homogenous subgroups (Table 1).

Table 1. Classification of poor quality ground water

Water quality	ECiw (dS m^{-1})	SARiw $(mmol^{-1})^{1/2}$	RSC (meq l^{-1})
A. Good	<2	<10	<2.5
B. Saline			
i. Marginally saline	2-4	< 10	<2.5
ii. Saline	> 4	< 10	<2.5
iii. High-SAR saline	> 4	> 10	< 2.5
C. Alkali water			
i. Marginal alkali	<4	<10	2.5-4.0
ii. Alkali	<4	<10	>4.0
iii. Highly alkali	variable	>10	>4.0

Poor Quality Ground Water Resources

In India so far, no systematic attempts have been made to arrive at the estimate of poor quality ground water resources. However, some predictions about use of poor quality water in various states are given in Table 2. The CGWB (1977) approximated that the total area underlain with the saline ground water (EC>4 dS m^{-1}) is 193,438 km^2 with the annual replenishable recharge of 11,765 M m^3 Yr^{-1}, leaving aside minor patches.

Table 2. Use of Poor quality ground water in various states of India

State	Utilizable ground water resources for irrigation in net terms (M ha-m Yr^{-1})	Net draft (M ha-m yr^{-1})	Level of ground water development (%)	Use of poor quality water (M ha-m Yr^{-1})	Area underlain by saline (EC>4dSm^{-1}) (km^2)
Punjab	1.47	1.67	98	0.68	3058
Haryana	0.86	0.72	76	0.47	11438
Uttar Pradesh	6.31	2.98	42	1.42	1362
Rajsthan	0.95	0.77	73	0.65	141036
Bihar	2.06	0.82	36	NA	NA
West Bengal	1.77	0.63	32	NA	NA
Delhi	0.01	0.01	120	NA	140
Gujarat	1.56	0.85	49	0.26	24300
Karnataka	1.24	0.45	33	0.17	8804
Tamilnadu	2.02	1.40	63	NA	3300
Madhya Pradesh	2.66	0.73	25	0.20	NA
Maharashtra	2.29	0.88	35	NA	NA
Andhra Pradesh	2.70	0.78	26	0.25	NA
Total (India)	32.63	13.50	37		193438

Source: Minhas *et al., 2004*

Management Options for Saline Water Use

Research studies at various centers in different agro-climatic zones of the country have yielded valuable concepts and viable technologies for the sustainable irrigation with poor quality water. It has been established that the success with poor quality water irrigation can only be achieved if factors such as rainfall, climate, water table, and water quality characteristics, soils and crops are integrated with appropriate crop and irrigation management practices. The available management options mainly include irrigation, crop, chemical and other cultural practices but there seems to be no single management measure to control salinity and sodicity of irrigated soil. Instead several management practices interact with each other and should be considered in an integrated manner. In this paper, however, different management options have been described separately as under.

Crop Management

Selection of Crops

For successful utilization of saline water, crops which are semi-tolerant to tolerant such as mustards, wheat and cotton as well as those with low water requirement are recommended. Crops such as rice, sugarcane and berseem, which require liberal water use, should be avoided. In low rainfall areas (<40 cm/annum), mono–cropping is recommended for maintaining salt balances. Salt tolerance limits of cereals, oil seeds, vegetables, and pulses developed in different ecological regions of India are available in Table-3. The choice of crops for a given soil and water salinity condition can be made from this data. Some other specific recommendations related to crop selection and management are as under:

Table 3. Salinity limits of irrigation water for agricultural crops

Crops	Soil texture	Pervious crop	ECiw (dS/m) for yield (%)	
			90	75
		Cereals		
Wheat	Silty clay loam	Sorghum	3.4	7.0
	Sandy loam	Bajra	6.6	10.4
	Loamy sand	Fallow	8.3	11.7
	Sand	Fallow	14.0	16.1
Barley	Sandy loam	Fallow	7.2	11.3
Rice	Silty clay loam	Rice	2.2	3.9
Maize	Clay loam	Wheat	2.2	4.7
Pearl-millet	Sandy loam	Wheat	5.4	9.0
Italian-millet	Sand	Sunflower	2.4	4.6
Sorghum	Sandy loam	Mustard	7.0	11.2
Sorghum fodder	Sandy loam	Berseem	5.2	10.2
		Oilseeds		
Mustard	Sandy loam	Sorghum	6.6	8.8
Safflower	Silty clay loam	Maize	3.3	6.8
Sunflower	Sandy loam	Mustard	3.5	7.2
Groundnut	Sand	Italian-millet	1.8	3.1
Soyabean	Silty clay loam	Mustard	2.0	3.1
		Pulses/Legumes		
Pigeon pea	Sandy loam	Onion	1.3	2.3
Clusterbean	Sandy loam	Variable	3.2	4.5
Cowpea	Loamy sand	Variable	8.2	13.1
Berseem	Sandy loam	Sorghum	2.5	3.2
		Vegetables		
Onion	Sandy loam	Pigeonpea	1.8	2.3
Potato	Sandy loam	Okra	2.1	4.3
Tomato	Sand	Variable	2.4	4.1
Okra	Sandy loam	Potato	2.7	5.6
Chillies	Sand	Variable	1.8	2.9
Brinjal	Sand	Variable	2.3	4.1
Fenugreek	Sandy loam	Potato	3.1	4.8
Bitter gourd	Sand	Variable	2.0	3.4
Bottle gourd	Sand	Variable	3.2	4.5

Growth stages: All crops do not tolerate salinity equally well at different stages of their growth. For example, germination and early seedling establishment are the most critical stages followed by the phase changes from vegetative to reproductive i.e. heading and flowering to fruit setting. Therefore, the use of saline water should be avoided during initial stages of crop growth.

Crop cultivar: In addition to intergenic variations, crop cultivar also vary in their tolerance to salinity. Such cultivars have been identified on their rating for high yield potential, salt tolerance and stability under saline environments and are included in Table 4.

Table 4. Promising cultivars for saline and alkaline environments

Crop	Saline environment	Alkali environment
Wheat	Raj 2325, Raj 2560, Raj 3077, WH 157	KRL 1-4, KRL19, Raj 3077, HI1077, WH 157
Pearl-millet	MH269, 331, 427, HHB-60	MH 269, 280, 427, HHB 392
Mustard	CS416,CS330,-1, Pusa Bold	CS15, CS52, Varuna, DIRA 336, CS 54
Cotton	DHY 286, CPD 404, G 17060, GA,	HY6, Sarvottam, LRA 5166 JK276-10-5, GDH 9
Safflower	HUS 305, A-1, Bhima	Manjira, APRR3, A300
Sorghum	SPV-475, 881, 678, 669, CSH 11	SPV 475, 1010, CSH 1, 11, 14
Barley	Ratna, RL345, RD103, 137, K169	DL4, 106, 120, DHS 12

Cropping sequence: Cropping sequence is another critical step in mitigating saline conditions. The recommended cropping sequence for saline conditions are pearl millet –barley, pearl millet-wheat, pearl millet-mustard, sorghum-wheat or barley-sorghum-mustard, cluster bean – wheat or barley and cotton- wheat or barley. The pearl millet-wheat, pearl millet-barley, pearl millet-mustard, sorghum (fodder)-wheat and sorghum (fodder)-mustard cropping sequences are more remunerative in saline soils. Cotton based cropping sequence are not beneficial since the yield of the winter crops that follow cotton are usually low. In areas with water scarcity, mustard could replace wheat in the cropping sequence since its water requirement is low compared to wheat.

Ionic Composition Effects

Chlorides, being more toxic tend to reduce the tolerance limits of crops to the use of saline water by 1.2 – 1.5 times as compared with sulphate rich water (Manchanda, 1998). Similarly, more salts tend to accumulate in soils when irrigated with water of high SAR and thus tend to reduce the limits of saline water use.

Tree Species

In cases where it is neither feasible nor economical to use saline water for crop production, such water can be used to raise tree species especially on lands those are already degraded. The preferred choice of species should be *Azadirachta indica*, *Acacia nilotica*, *A. tortilis*, *A. farnesiana*, *Cassia siamea*, *Eucaluyptus tereteerms*, *Feronia limonia*, *Prosopis juliflora*, *P. cineraria*, *Pithecellobium dulce*, *Salvadora persica*, *S. oleoides*, *Tamarix*.

Medicinal Plants

Some medicinal plant such as Isabgol (*Plantag oovata*), Aloe and Kalmeg have also been found promising under saline irrigation conditions as an alternative to arable crops.

Water Management

Irrigation and Leaching Management

As each irrigation with saline water results in addition of a certain amount of salts to the soil, salts may gradually accumulate in the root-zone to detrimental levels and cause reduction in crop yields if no leaching takes place. However, proper irrigation and leaching practices can prevent excessive accumulation of salts in the root zone. The following suggestions may be helpful.

- Arid areas would need 15 to 20 percent more water to be applied as irrigation for meeting out the leaching requirements. To maximize the benefit from enhanced quantity of irrigation water, attempts should be simultaneously made to minimize the water applied i.e. saline irrigation should be applied more frequently. Nevertheless, in areas with rainfall more than 400 mm and having monsoon type of climate, no extra leaching is usually required and the conventional irrigation practices may be followed. In the years of sub-normal rainfall, a heavy pre-sowing irrigation with saline water should be applied so that the salts accumulated during the preceding *rabi* season are pushed beyond the root-zone.
- The distribution of water and salts in soils vary with the method of irrigation. A shift towards micro-irrigation systems such as drip and sprinklers, where a better control on salt and water distributions can be achieved, hold promise for enhancing the use efficiency of saline water especially for high value crops (Table 5). Pre-emergence application of saline water through sprinklers, helps to keep soluble salt concentrations low in seedbed during germination and thus better establish the crop. Some of the indigenous alternative to drips on micro scale are the use of pitchers and specially designed earthen pots, however their feasibility on field scale remain untested.
- In the case of saline water logged soils provided with sub-surface drainage, the system can be beneficially employed to induce crop water use from shallow water table through controlled drainage in *rabi* crops and thus reduce the requirement of irrigation water.

Conjunctive Use of Saline and Canal Water

Often water of more than one quality is available at the same location. One such situation commonly arises when farmers have access to limited supplies of canal water along with saline ground water. The existing fresh and saline water supplies could be suitably combined in several ways. First option is to blend the two supplies such that the salinity attained after mixing is within the permissible limits of crop tolerance. The mixing of two water supplies from canal and tubewell also helps in improving the stream size and thus enhances the uniformity of irrigation especially in sandy soils.

Table 5. Yield and water use efficiency under different irrigation methods

Crop	Average yield (Mg ha^{-1}) for irrigation method			
	Surface method		Sprinkler method	
	CW*	SW*	CW	SW
Wheat (1976-79)	4.00 (97)**	3.62 (83)	3.69 (107)	3.54 (97)
Barley (1980-82)	3.51 (147)	2.32 (98)	3.48 (159)	2.59 (117)
Cotton (1980-82)	2.30	1.71	2.28	1.34
Pearl millet (1976-78)	2.38	2.07	2.54	1.50
		Drip Method		
		Surface	Subsurface	Furrow
Radish (EC_{water} 6.5 dS m^{-1})		15.7 (17.5)	23.6 (26.2)	9.9 (8.7)
Potato (4 dS m^{-1})		30.5 (93.5)	20.8 (78.5)	19.2 (53.6)
Tomato (10 dS m^{-1})		59.4	43.9	
Tomato (4 dS m^{-1})		42.6	36.9	

*CW- Canal water, SW-Saline water
** Figure in parenthesis denote water use efficiency (Kg/ha-cm).
Source: Aggarwal and Khanna (1983); Singh et al. (1978); AICRP-Agra (2002)

- Application of the two waters separately, if available on demand, can be done either to different fields, seasons or crop growth stages so that the higher salinity water is avoided at sensitive growth stages of the crops. As the germination and seedling establishment stages have been identified as the sensitive stages in most crops, better quality water should be utilized for pre-sowing irrigation and early stages of crop growth. Then a switch over to poor quality water can be made when the crops can tolerate higher salinity. In the seasonal cyclic use, non-saline water is used for salt sensitive crops or in the initial stages of tolerant crops to leach out the accumulated salts from irrigation with salty water to previously grown tolerant crops. Cyclic uses i.e. irrigating with water of different qualities separately offers both operational and performance advantages over mixing.
- For skimming of fresh water floating over seawater in coastal sandy soils, conventional *"Dorouv"* system has been improved with specially designed sub-surface water harvesting system that can irrigate up to 3-5 ha land (Raghu-Babu, 1999).

Nutrient Management

Fertilizers

Application of fertilzers is important for obtaining good yields with saline irrigation.

- Response to applied nitrogen is rather reduced under saline irrigation. Thus, additional doses of nitrogenous fertilisers, though do not materially change salinity tolerance but are recommended to compensate for volatilisation losses.
- Soils irrigated with chloride rich water respond to higher phosphate application, because the chloride ions reduce availability of soil phosphorus to plants. The

requirement of the crop for phosphoric fertilizers is, therefore, enhanced and nearly 50 per cent more phosphorus than the recommended dose under normal conditions should be added, provided the soil tests low in available phospourous.
- For sulphate rich water, no additional application of phosphatic fertilisers is required and the dose recommended under normal conditions may be applied.
- For micro-nutrients such as zinc, the recommended doses based on soil test values should be applied.

Farmyard Manure (FYM)

FYM and other organic manures not only have the nutritive value, they also play an important role in structural improvements. This further influences leaching of salts and reduce their accumulation in the root zone. The other advantage of FYM in saline water irrigated soils are in terms of reducing the volatilisation losses and enhancing the nitrogen-use efficiency. Retention of nutrients in organic forms for longer periods also guards against leaching and other losses. In the context of the advantages of FYM and other organic manure, they should be applied to the maximum possible limit.

Cultural Practices

Owing to reduced germination, often a poor crop stands in fields irrigated with saline water. Thus, to ensure better populations following measures are suggested:
- Reduce inter/intra row spaces and use 20-30% extra seed than under normal conditions.
- Dry seeding and keeping the surface soil moist through sprinkler or post-sowing saline irrigation helps in better establishment of crops.
- Modifications in seedbed e.g. sowing near the bottom of the furrows on both sides of the ridges, applying irrigation in alternate row, and to seed on the north-east side of the ridges, is recommended. For the larger seeded crops, the seeds can be planted in the furrows. The furrow irrigation and bed planting system (FIRB) has been found better than conventional planting in cotton / pearl millet –wheat rotations.
- Adoption of measures for better intake of rainwater (tillage to open up soil) and its conservation in soil via checking unproductive evaporation losses (soil/ straw mulching) is recommended during monsoon season.

Management Options for Use of Alkali Water

Consistent efforts have been made at different research centers in the country to devise ways for the safe utilization of sodic water to raise agricultural crops. With scientific advances, the basic principles of soil-water-plant systems are now fairly well understood and advocate specialized soil, crop and irrigation management practices for preventing the deterioration of soil to levels which limit the crop productivity. Some such management measures for controlling the built up of ESP and maintaining the physical and chemical properties of sodic water irrigated soils are being discussed below.

Land Levelling and Rain Water Conservation

Proper land levelling and provision of 30-40 cm high strong bunds for capturing and retaining rainwater are the essential prerequisites for managing the land irrigated with sodic water. The surface soil should be protected against beating action of raindrops, which can be achieved through ploughing the field in between rains. This practice, besides increasing intake of rainwater helps in controlling the unproductive losses of water through weeds and evaporation. These practices also promote uniform salt leaching and self-reclamation through the dissolution of soil calcium carbonate.

Crop Selection

The guiding principle for choosing the right kind of crops and cropping patterns suitable for a particular sodic water is to select only those crops whose sodicity tolerance limits are lower than the expected soil sodicity (ESP) to be developed by the use of that water. Under average conditions of water use, the expected root zone sodicity can be approximated by 1.5 ´ SARiw in fallow- wheat, 2.0 ´ SARiw in millet- wheat and 3.0 ´ SARiw in rice-wheat cropping sequences. Thus, based on the expected ESP to be developed, the suitable crops can be chosen from the list of sodicity tolerant crops given in Table 6 & 7. Since use of sodic water requires repeated application of gypsum, it is advisable to select only tolerant and semi tolerant crops and their varieties having low requirements of water such as barley, wheat, mustard, oats, bajra and sorghum. The choice of promising cultivars can be made from the list given in Table 4. The other guidelines pertinent to selecting crops suitable for sodic water are :

- In low annual rainfall areas (< 400 mm) if the good quality canal water is not available, it is advisable to keep the fields fallow during *kharif* season. During *rabi*, only tolerant and semi-tolerant crops such as barley, wheat and mustard should be grown.
- For areas having rainfall >400 mm per annum, jowar-wheat, guar-wheat, bajra-wheat and cotton-wheat rotations can be practised, provided it is ensured that sowing, particularly of *kharif* crops is done with rain water or good quality canal water. Besides, not more than 2 to 3 irrigations should be applied with sodic water in the *kharif*.
- For areas having annual rainfall >600 mm in the rice-wheat belt of alluvial plains, rice-wheat, rice-mustard, sorghum-mustard, and *dhainacha* (green maure)-wheat rotations can be practiced with gypsum application.
- Alternating sodic water use between moderate water requiring crop rotation and a low water requiring crop helps in checking faster sodicity development by RSC bearing water.
- Sodic water should not be used for growing summer crops in the month of April to June.

Table 6. Relative tolerance of different crops to sodicity of soils

ESP Range*	Crops
10-15	Safflower, peas, lentil, pigeon pea, *urdbean*, banana
16-20	Bengal gram, soybean, papaya, maize, citrus
20-25	Groundnut, cowpeas, onion, pearl-millet, guava, *beal*, grapes
25-30	Linseed, garlic, guar, palma rosa, lemon grass, sorghum, cotton
30-50	Mustard, wheat, sunflower, *ber, karonda, phalsa*, vetiver, sorghum, *berseem, senji*
50-60	Barley, sesbania, paragrass, Rhoades grass
60-71	Rice, sugarbeat, *karnal grass*

*Threshhold ESP

Table 7. ESP tolerance of crops in alkali soils and irrigated with alkali water

Crop	Soil under reclamation			Alkali water irrigation		
	ESP_t^*	Slope	ESP_{75}^{**}	ESP_t	Slope	ESP_{75}
Cotton	—	—	—	14.9	1.3	34.1
Pearl millet	13.6	2.6	23.2	6.1	1.3	25.3
Rice	24.4	0.9	52.1	20.1	1.6	35.7
Wheat	16.1	2.1	28.0	16.2	1.9	29.38

*Threshhold ESP** ESP for 75% yield.

Use of Amendments

Sodic water can be safely and economically used after treating them with calcium bearing amendment such as gypsum. The agricultural grade gypsum can either be added to soil or applied in water through specially designed gypsum beds. Both methods are equally effective in neutralizing the RSC of water and its adverse effects. Acidic amendment like pyrites can also be used for amending the deleterious effect of high RSC water both as soil application and as pyrite bed. The quantity of gypsum applied should be known based on the analysis of water and irrigated soil. It depends on the RSC of water, extent of soil deterioration, and the water requirements of the intended crops and cropping system. However, following guidelines can be of additional help in deciding the need and quantity of amendments required for different sodic water use situations:

Gypsym Application

- Gypsum is generally not needed on well-drained light textured soils in fallow-wheat rotation. In double cropping, however, its application at the rate of 25% - 100% Gypsum Requirment (GR) of water has been reported to boost crop yields (Manchanda, et. al. 1985). Yadav *et al*. (1991) in another study has reported that addition of gypsum at the rate of 50% gypsum requirement of a loamy sand soil was found sufficient to grow even the sensitive *kharif* crops like pearl millet, *moongbean, urdbean*, cowpea and clusterbean in the presence of 600 mm rainfall.

- In relatively high annual rainfall regions (> 600 mm), gypsum application equivalent to 50% of gypsum requirement of water annually was found sufficient to sustain 8-9 Mg /ha of paddy and wheat yields (Sharma and Minhas, 2001) provided the final pHs of surface soil did not exceed 9.0
- Occasional application of gypsum at the rate of 1-2 tons/ha before rainy season is also recommended to offset infiltration problems created by high SAR saline water (SAR>20) particularly on heavy textured soils vulnerable to infiltration reductions.

Method and time of gypsum application in soil: Application of gypsum in the soil is easier than applying it through water. The powdered gypsum may be applied through broadcast in the requisite quantity on a previously leveled field and mixed in shallow depth of 10 cm with a cultivator or disking. The best time for application of gypsum is after the harvest of *rabi* crops, preferably in the month of May or June, if some rain has occurred. Otherwise, its application should be postponed till the first good monsoon showers are received.

Gypsum can be applied in the standing water also. The soil should be subsequently ploughed upon attaining proper soil moisture condition. Gypsum applied after the harvest of a r*abi* crop will also help in considerable improvement of the soil prior to the on set of *kharif* season. Pyrites has also been used for amending the deleterious effects of high RSC water. Pyrite application once before the sowing of wheat has proved better than its split application at each irrigation or mixing it with irrigation water (Chauhan et al., 1986).

Gypsum bed: An alternative approach to reclaim sodic water is to pass it through a specially designed chamber filled with gypsum clods. Using this approach, water can be reclaimed before it enters the field. The gypsum chamber consists of a brick-cement-concrete chamber, the size of which depends on tubewell discharge and RSC of water. The chamber is connected to a water fall box on one side and to water channel on the other side. A net of iron bars covered with wire net (2 mm x 2 mm) is fitted at a height of 10 cm from the bottom of the bed. With a little modification, the farmers can also convert their tube well waterfall chamber in to gypsum chamber. Sodic water flowing from below dissolves gypsum placed in chamber and gets reclaimed. By this method, the RSC of water was reported to be reduced from 5. 5 to 1.9 me/l by passing it through a chamber of size 2.0 x 1.5 x 1.0 m with tube well discharge of 6l/sec in studies conducted at HAU, Hisar.

Gypsum bed method is however, not suitable for reclaiming a very high RSC water (> 12 me/l) because in that case the size of the chamber becomes too large and the quantity of gypsum required to fill the chamber is too high. It has also been observed that the gypsum bed water quality improvement technique may not dissolve > 8 me/l of calcium. The response of crops to the application of equivalent amounts of gypsum, either by passing the water (RSC 9 meq/l) through gypsum beds where the thickness of bed was maintained at 7 and 15 cm, or the soil application of gypsum is presented in Table 8. Though crops under both rotations (paddy-wheat, sorghum-mustard) responded to the application of gypsum in either of the methods, overall response of crops was slightly more in case of sodic water which was ameliorated (3-5 meq/l) after passing through gypsum beds. Thus, it can be argued that gypsum bed technique can help in efficient utilization of gypsum.

Table 8. Average yields (Mg/ha) under paddy-wheat, mustard-sorghum (1993-2003) rotations and soil properties* as affected by equivalent doses of gypsum applied either to soil or passing sodic water through gypsum beds

Treatment	Paddy	Wheat	pH	ESP	Mustard	Sorghum	pH	ESP
Control (T_1)	3.08	2.68	9.6	66	2.27	1.18	9.5	61
Gypsum through beds								
3.3 meq/l (T_2)	3.97	3.73	8.0	19	3.06	1.98	8.0	25
5.2 meq/l (T_3)	4.24	3.93	8.0	18	3.18	2.13	8.0	24
Equivalent soil application								
As in T_2 (T_4)	4.31	3.71	8.2	20	2.86	1.92	8.0	26
As in T3(T_5)	4.52	3.89	8.1	20	3.00	2.05	8.1	24
LSD(p=0.05)	0.43	0.46			0.38	0.24		

* At the harvest of *rabi* (2002-03) crops. (AICRP Saline Water, 2002)

Irrigation Management

Conventional irrigation practices such as basin irrigation could be adopted to manage alkali water. Emphasis should be to minimize the irrigation with alkali water as deterioration of soil directly depends on the quantities of irrigation water. The 'alkali hazard' is reduced considerably, if the water is used alternatively or mixed with canal water. Besides reducing the gypsum requirement of soil, conjunctive use of alkali and canal water also helps in bringing more area under protective irrigation and also in controlling rise in ground water table and associated problems. Canal water should preferably be applied during initial stages including pre-sowing irrigation to boost establishment of crops. Studies have sown that when sodic water was used in cyclic mode equal to with canal water, yield of both the paddy and wheat crops were maintained with canal water except in the CW-2SW mode (Table 9).

Table 9. Effect of cyclic use of sodic and canal water on soil properties and crop yields

Water quality/mode	adj. SAR*	pH	ESP	Average yield (Mg/ha)	
				Rice	Wheat
Canal water (CW)	0.3	8.2	4	6.78	5.43
Sodic water (SW)	22.0	9.7	46	4.17	3.08
2 CW-1SW	8.9	8.8	13	6.67	5.22
1 CW-1SW	12.8	9.2	18	6.30	5.72
1 CW-2SW	18.5	9.3	22	5.72	4.85

	ECw dS/m	Ca	Ca+Mg	RSC	SAR	adj SAR
		…….(meq/l)……..				
CW	0.25	1.6	2.1	nil	0.3	0.4
SW	1.35	0.4	0.9	10.1	13.5	26.7

* After accounting for 828 and 434 cm of irrigation and rainwater, respectively.
* Source : Bajwa and Josan (1989)

Nutrient Management

Fertilizer Application

Since sodic water cause a rise in soil pH that leads to greater nitrogen losses through volatilization and denitrification, extra nitrogen may have to be added to meet the requirement of the crops. Similarly, the availability of zinc and iron is also low due to their precipitation as hydroxides and carbonates. Some beneficial tips as regards fertilizer use are:

- Application of 25% extra nitrogen is needed as compared to the normal conditions.
- Zinc sulphate @ 25 kg per ha should be added, particularly for the r*abi* crops.
- Phosphorus, potassium and other limiting nutrients may also be applied on the basis of soil test values.
- Some sodic water may be rich in nutrients such as nitrogen, potassium and sulphur. Water should be analysed and the fertiliser dose of concerned nutrient reduced accordingly.

Addition of Organic Materials

It is generally accepted that addition of organic materials improve sodic soils through mobilization of inherent Ca^{2+} from $CaCO_3$ (Calcium Carbonate)and other minerals by organic acids and increased pCO_2 in soils. The solublized Ca^{2+} in soil replaces Na^+ from the exchange complex. Reclamation of barren alkali soils by addition of organic materials has been widely reported. However for soils undergoing sodication, some disagreement exist in literature regarding the short–term effects of organic matter on the dispersion of sodic soil particles (Gupta et.al, 1984). Nevertheless, majority of the available reports still suggest the overall beneficial and positive role of FYM towards improving soil properties and crop yields. The response of organic sources also varies with the nature of organic matter added. Sekhon and Bajwa (1993) reported the effectiveness of different materials as: paddy straw > green manure> FYM. Moreover, with the mobilization of Ca^{2+} during decomposition of organic materials, the quantity of gypsum required for controlling the harmful effects of sodic water irrigation can be considerably decreased. Thus, occasional application of organic materials should help in sustaining yields of crops irrigated by sodic water.

Water Quality Guidelines

Based on the experiences of using saline and sodic water in the field and results from different experiments available on the subject, some guidelines have been prepared for water quality. These guidelines have been prepared at CSSRI, Karnal in consultation with the scientists from HAU, Hisar and PAU, Ludhiana which might be helpful for utilizing water more efficiently. These guidelines emphasize the long- term influence of water quality on crop production, soil conditions and farm management. These guidelines assume that all the rainwater received in the field is being conserved to impart leaching and desalinizing the upper root zone. The guidelines for Saline water RSC<2.5 meq/litre is listed in Table 10(a) and for alkali water (>2.5 meq/litre)is give in Table 10(b).

Table 10(a). Guidelines for using poor irrigation water

A. Saline water (RSC < 2.5 meq/l)

Soil texture (% clay)	Crop tolerance	Upper limits of ECiw (dS/m) in rainfall regions (mm)		
		350	350-550	550-750
Fine(> 30)	S	1.0	1.0	1.5
	ST	1.5	2.0	3.0
	T	2.0	3.0	4.5
Moderately fine(20-30)	S	1.5	2.0	2.5
	ST	2.0	3.0	4.5
	T	4.0	6.0	8.0
Moderately coarse(10-20)	S	2.0	2.5	3.0
	ST	4.0	6.0	8.0
	T	6.0	8.0	10.0
Coarse(< 10)	S	- -	3.0	3.0
	ST	6.0	7.5	9.0
	T	8.0	10.0	12.5

Note: S: sensitive, ST: semi-tolerant and T: tolerant crops.

These guidelines identify special consideration for saline water such as:

- Use gypsum when saline water (having SAR > 20 and/or Mg/Ca ratio > 3 & rich in silica) induces water stagnation during rainy season and crops grown are sensitive to it.
- Fallowing during rainy season is helpful when SAR > 20 and water of higher salinity are used in low rainfall areas.
- Additional phosphatic fertilization is beneficial, especially when C1/SO4 ratio in water is > 2.0.
- Canal water preferably is used at early growth stages including pre-sowing irrigation for conjunctive use with saline water.
- Putting 20% extra seed rate and a quick post-sowing irrigation (within 2-3 days) will help better germination.
- When ECiw < ECe (0-45 cm soil at harvest of rabi crops), saline water irrigation just before the onset of monsoon will lower soil salinity and will raise the antecedent soil moisture for greater salt removal by rains.
- Use of organic materials in saline environment improves crop yields.
- Accumulation of B, F, NO3, Fe, Si, Se and heavy metals beyond critical limits proves toxic. Expert advice prior to the use of such water may be obtained.
- For soils having (i) shallow water table (within 1.5 m in *kharif*) and (ii) hard sub-soil layers, the next lower ECiw/alternate mode of irrigation (canal/saline) is applicable.

Table 10 (b). Guidelines for irrigation water

B. Alkali water (sodic) with RSC > 2.5 meq/l and ECiw < 4.0 dS/m

Soil texture (% caly)	Upper limits of SAR √(m mole/l)	Upper limits of RSC, meq/l	Remarks
Fine (>30)	10	2.5-3.5	1. Limits pertain to *kharif* fallow – *rabi* crop rotation when annual rainfall is 350 –550 mm.
Moderately fine (20-30)	10	3.5-5.0	2. When the water have Na < 75%, Ca+Mg >25% or rainfall is > 550mm, the upper limit of the RSC range becomes safe.
Moderately coarse (10-20)	15	5.0-7.5	3. For double cropping, RSC neutralization with gypsum is essential based on quantity of water used during the *rabi* season. Grow low water requiring crops during *kharif*. Avoid growing rice.
Coarse (<10)	20	7.5-10.0	

Textural criteria should be applicable for all soil layers down to at least 1.5 m depth. In areas where ground water table reaches within 1.5 m at any time of the year or a hard subsoil layer is present in the root zone, the limits of the next finer textural class should be used. Fluorine is at times a problem and limits should be worked out.

Policy Guidelines

In order to implement various technological options for enhancing the use of saline sodic water under real world field situations, the management strategies must be backed by strong policies on water management. In this section some of the policy guidelines are outlined:

Water Quality Monitoring Network

At present no systematic data collecting network is available in most developing countries. Data are gathered in random fashion and there is no mechanism for their proper storage. Water quality management must form an integral part of overall water management objectives at the basin or canal command level. Thus, systematic database must be generated on water quality through network of stations in the basin or irrigation commands by strengthening the existing central and state level agencies.

Modifications in Surface Water Delivery Schedules

Consistent with the irrigation system water supplying capacity, release from reservoir based schemes should be modified to deliver more water during pre-sowing irrigation. This is essentially a case of intra-seasonal modification in water delivery scheduling. Policy interventions are required to ensure canal water supplies at sowing time of crops in saline irrigated areas.This would encourage farmers to bring more area under cultivation leading to enhanced productivity.

Ground Water Pumping Pricing

The present scenarios of providing substantial public subsidies in terms of free electricity is not only costing the exchequer but also leading to huge withdrawl of ground water in areas underlain with better quality water. Thus, a careful assessment of costs, public information, and education on costs of water services and consequences of subsidies are important for rational pricing strategies. Pricing of electricity has to be differential. Areas endowed with better quality water may be charged higher electricity tariff so that 'water save' concept could be given practical shape whereas area disadvantaged with poor quality water may be provided with additional subsidies for the promotion of judicious use of electricity. Moreover, the electricity networks in the saline areas should be made more intensive as the number of tube wells required are more in poor aquifers as compared with the good aquifer.

Subsidies on Amendments

The farmers in areas underlain with alkali water further have to incur additional recurring costs on the amendments such as gypsum for sustaining crop productivity. Though the state governments provide for the subsidies on gypsum for alkali soil reclamation these are not rendered in alkali water areas. This matter needs to be addressed as more farmers are shifting to paddy-wheat cultivation in such areas, and demand for amendments are increasing.

Promoting Conjunctive Use

Technically sound and economically viable technologies are available for conjunctive use of surface and poor quality ground water that not only promote the latter's use but also can help maintain overall salt and water balances in the basins. However, so far due to regional/state level conflicts, the better quality surface water resources are not being made available for regions already suffering from the twin problems of scarcity as well as saline ground water resources. Such issues should be tackled on priority to give thrust to agricultural production in the affected areas.

Further Subsidies on Micro-irrigation Systems/Dorouv Technology

Development of micro-irrigation systems including the use of drips, which of course are more capital intensive is considered to be the major innovation to enhance the use of low quality water. Though subsidies are given for promoting these techniques, further incentives are required for installation of such water saving irrigation systems. Farmers nedd to be trained also in marketing opportunities for selling their produce. A case in point is grapes which was introduced on large scale in Hissar and Sirsa districts of Haryana without any proper processing and market mechanisms in place. As a consequence, farmers suffered heavy losses and abandoned the crop. On the other hand in Bijapur where organised marketing and processing facilities are functional, the farmers are using saline water with drip irrigation systems.

Participatory Planning

In order for policy guidelines to be effective, participatory planning, by including the farmers is critical. Especially the planning process should be restructured for improving the services and promoting user's participation at the lower levels of the irrigation systems. For example, includ ing group of farmers at the tail end of the irrigation system, who make use of poor quality water and are usually left out of the planning exercises.

Training Needs

Existing staff skills need to be upgraded and new expertise introduced for water quality monitoring and management. The other alternative is to acquire new capabilities through recruitment of specialists in water quality management to address the newly emerging challenges.

Recharge Measures

Cost effective artificial recharge measures have to be adopted on the basis of water balance studies in the sub-basins. Surface water bodies and canal systems have to be fully utilised for achieving recharge through potential zones especilly during spill season.

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Realizing the Potential: Using Pumps to Enhance Productivity in the Eastern Indo-Gangetic Plains

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Abstract

Eastern Indo-Gangetic Plain (EIGP) comprising of eastern Uttar Pradesh, Bihar and West Bengal in India, Nepal tarai and plains of Bangladesh, though endowed with rich water resources has very low produtivity. This region is characterized as "High potential low productivity" area. Though, the ground water development in the region has increased substantially during the last decade (19.2% and 24.2% in 1993 to 33.2 and 32.2% in 1998, respectively in the two states of Bihar and West Bengal) its utilization is poor owing mainly to improper irrigation scheduling and selection of pumps and poor pump efficiencies, unreliable energy supply, and lack of information to users. The tail reaches in most of the canal command also depend on groundwater irrigation. Pump is the predominant device used for lifting of groundwater. In the past two to three decades, pump technology has been spreading rapidly resulting in crucial transformation of the irrigated agriculture in areas such as EIGP that previously had been unable to take full advantage of the "green revolution" technology due to lack of irrigation water. The recent adoption of pump technology was far more rapid in Bangladesh, but much slower in Bihar and Nepal tarai. Density of the pumping unit in the eastern region (around 105 pumps / thousand ha) is far low as compared to agriculturally developed states–such as Punjab (225 pumps / thousand ha in 1993-94) and Haryana (148 pumps/thousand ha). This not only resulted in under utilization of ground water but also poor realization of benefits from the groundwater.

Small and highly fragmented land holdings, unreliable / erratic energy supplies, poor economic conditions and lack of infrastructure facilities are some of the reasons for under utilization of groundwater. In the EIGP, use of diesel operated pumps is predominant, as more than 90% of the pumps are diesel operated. Efficiency of pumping units is also a serious concern. Small and cost effective interventions, e.g. improvement in fittings and foot / reflux valves, can substantially increase pump efficiency. Conjunctive use of groundwater in canal command has been demonstrated to enhance the crop yields under rice-wheat system by more than two folds and encourage groundwater utilization. Groundwater market is another opportunity, which needs to be explored in large scale to provide irrigation facilities to small farm holders who can not afford tube wells/shallow tube wells and/or find it uneconomical to own it. Groundwater markets have grown in Bangladesh, West Bengal, in parts of eastern U.P. and North Bihar to a certain extent. There are also evidences to support the concept and functioning of community/group tube

wells operated by groups of small and marginal farmers in backward regions of eastern U.P. (Deoria) and north Bihar (Vaishali).

The paper presents a brief description of various efforts made to enhance productivity in the EIGP together with challenges in groundwater management including cost effective and energy efficient technologies and participatory on-farm water management.

Introduction

Pumps are widely used for extracting groundwater and lifting water from surface systems for irrigation. Pumps and tube wells technology together with government policies on subsidizing credit and rural energy supplies have led to phenomenal growth of groundwater development in India. Groundwater abstraction structures have increased from 4 million in 1951 to nearly 17 million in 1997 (Chadha, 1999). Groundwater now contributes to about 60 per cent of irrigated agriculture in India. While in Bangladesh, 90 per cent of irrigation is from groundwater, mostly through tubewells in the private small-scale sector, and shallow tube wells account for 60 per cent of the total irrigated area (Bhuiyan, 2003). Effective utilization of pumps has potential to increase the agricultural productivity as it provides greater access to water when needed and is also a cheaper means of irrigation development as compared to canal irrigation. Groundwater has emerged as the primary democratic water source and an instrument of poverty alleviation in India's rural areas (Debroy & Shah, 2002). Rapid growth of pump technology has been resulting in a crucial transformation of irrigated agriculture in areas that were previously unable to take full advantage of the "green revolution" technology due to lack of irrigation water. The recent adoption of pump technology has been rather uneven, which was far more rapid in Bangladesh and West Bengal, but much slower in Bihar and Nepal *tarai*.

Eastern Indo-Gangetic Plains (EIGP) comprising of eastern UP, Bihar and West Bengal in India, Nepal tarai and Plains of Bangladesh are endowed with rich water resources as compared to Western Indo-Gangetic Plains (WIGP). Although, the level of groundwater development has shown increasing trend, however, it is far below the western IGP. Rice-wheat is the predominant cropping system in EIGP, with low level of productivity. For example, in Bihar, the combined rice-wheat productivity is 3.6 t/ha as against the national average of 4.7 t/ha. This region is, therefore, popularly known as "High Potential Low Productivity" area. Adoption of pumps and tubewells for groundwater utilization together with improved water management practices and energy efficient water delivery/devices hold potential for increasing agricultural productivity and livelihoods of poor farmers in the eastern IG Plains.

Overview of Indo-Gangetic Basin (IGB)

The Indo-Gangetic Basin (IGB) spans Pakistan, India, Nepal and Bangladesh and lies mostly in the Indus-Ganges-Brahmaputra plain, which extends 3,200 km between the mouth of the Ganges River, to the east, and that of the Indus, to the west. The basin, among the world's largest and most productive basins, forms the floor beneath the "roof of the world", the Himalayas. IGB provides the economic base for agriculture, forestry, fisheries, livestock, including urban and industrial water requirements for about a billion people. Given the diversity of agro-climatic, social and economic conditions in the four riparian countries and home to the earliest river valley (Indus valley) civilizations as well as the present-day economic dynamism taking off in South Asia, the basin is a study of contrasts and opportunities in all respects. The total basin area is 225.2 million ha and the net cropped area is 114 million ha. The population of IGB is 747 million as per 2001 census. Rural population in Bangladesh, India, Nepal and Pakistan is 79.9, 74.5, 86.0 and 68.0 per cent, respectively of the total population. About 30.5 percent population in IGB is below poverty line. High population growth rates in all countries remain a cause for concern in terms of water and food security, poverty alleviation and resource conservation. Around 91.4 percent of the annual water use is for agriculture purposes followed by 7.8 per cent for domestic use in IGB.

The per capita water availability in the Indian portion of the Indo-Gangetic basin under the projected water demand by 2025 is going to be reduced to the level that it will become a water stressed area (i.e. having per capita water availability < 1700 m^3). The level of groundwater development is more (77.7%) in Indus than in Ganges (33.5%) basin.

In general, the IGB exhibits high potential but with only low-to medium actual primary productivity of agriculture, forestry, fisheries, and livestock. However, conditions are extremely heterogeneous; as a result, the problems and challenges vary in the Upper Catchments (UC), Western Indo-Gangetic Plains (WIGP), and Eastern Indo Gangetic Plains (EIGP). The future strategy should be focused to check water table decline and enhance ground water recharge in the western IGB; ensure development and utilization of ground water in eastern IGB including multiple water use; conjunctive use of ground water – ground water, rain water, surface water and marginal quality water, ground water – energy nexus, water pricing, energy policies and institutional issues in ground water management and governance; and design of technologies to reduce groundwater pollution, and enhance water productivity.

Status of Ground Water Development in EIGP

Ground water development in the EIGP is quite low as compared to other parts of the country, while the recharging capacity is better due to good rainfall and alluvial soils. Only 19.2% of available ground water was developed in Bihar and 24.2% in West Bengal till 1993. This level rose to around 33% for both the states by 1998, which is far less than the safe exploitation level of 65%. Whereas in the WIGP states (Punjab and Haryana), the ground water development has already crossed the critical limit of 85% and in some of the pockets, ground water mining is occurring due to over-exploitation.

Ground water development is largely done through private resources, by individual farmers, group of farmers, or by some enterprise rather than government. However, government policies certainly have great impact, as evidenced by rapid growth of ground water development in eastern Uttar Pradesh as compared to other states of eastern India. This has been primarily due to a number of government policies, for example, free boring scheme and subsidy on other programmes which were offered to small and marginal farmers matching with their socio-economic needs (Ballabh and Choudhary, 2002).

The "Million Shallow Tubewell" scheme launched by the Government of India also created some impact in increasing the ground water utilization. Under this scheme, 377,111 shallow tubewells were to be dug out up to 2004-2005 in Bihar, out of which 56% of the target has been achieved by November 2004. Such efforts and government policies did help to some extent in increasing the ground water utilization.

Ground water level in EIGP is relatively high. Fig.1 shows the percent distribution of villages under different ranges of ground water depth. Although, the Bihar data includes plateau region of Jharkhand (undivided Bihar), even then more than 45% villages have ground water below 10 m. In West Bengal, 68% of villages have ground water below 10 m. This indicates the large potential of developing groundwater through shallow tubewells in the eastern region.

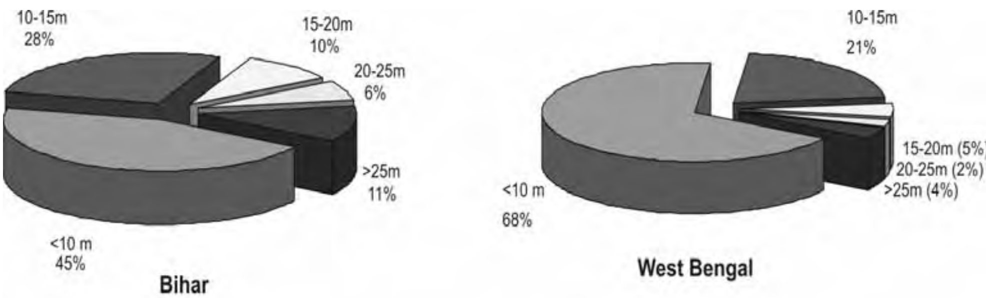

Figure 1. Distribution of number of villages in Bihar (undivided) and West Bengal under different range of depth of ground water level

Growth of Pumps

The number of pumps available in the eastern region is far less than those of Western IGP. The scenario for electrical pumps is shown in Fig.2. The electrical pumps available in 1998 in the eastern region were less than 20 per 1000 ha of net sown area as compared to 165 in southern region. As per minor irrigation census (1993-94), the pump density in Bihar and West Bengal was around 105 per 1000 ha, while it is 225 /1000 ha in Punjab (Fig.3). The number of diesel pumps are far more than electric pumps in Bihar and West Bengal, while the scenario is opposite for western IGB states. This is mainly because of government policy towards subsidizing the electricity and reliability/poor availability of electricity in eastern states with problems of high/low voltage, frequent breakdowns/cuts, etc. This compelled farmers to go for diesel pumps, whose operational cost is not subsidized and moreover availability of diesel in remote areas becomes problem. This is one of the major reasons of low pump density in eastern region. After 1990, the pump growth was much slower as nearly 1500 pumps were added each year in West Bengal and Bihar, while in smaller western IGB states such as Punjab and Haryana this was much higher (Fig.4).

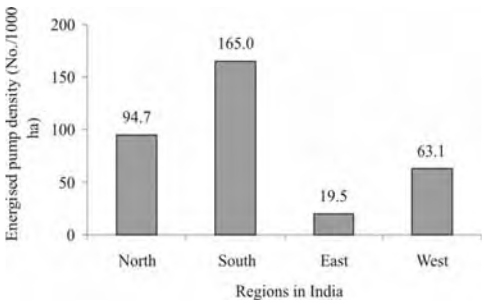

Figure 2. Electric pump density in India (1998)

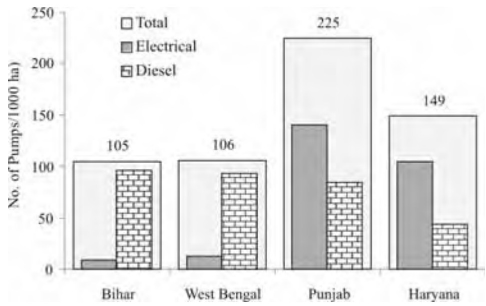

Figure 3. Density of electric and diesel operated pumps in selected states of IGP

In Bihar, the proportion of electricity consumption in agriculture sector increased steadily up to 20.4% of electricity generated / or supplied in the state (during 1991), but thereafter, it dropped to 12.5% during 1996 and remained at 14.3% even during 1999 (Fig. 5). As the electricity availability dropped, at several locations the electrical distribution network became defunct and the wires were stolen. In West Bengal, the consumption of electricity for agricultural purposes is less than 10%, and farmers mostly depend on diesel-operated pumps.

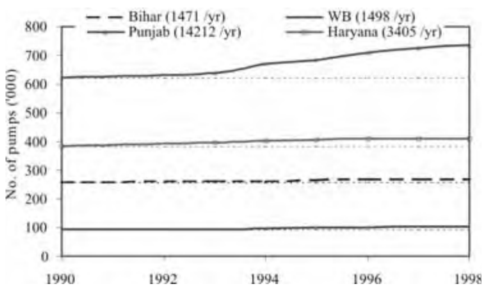

Figure 4. Growth of electric pumps between 1990 and 1998

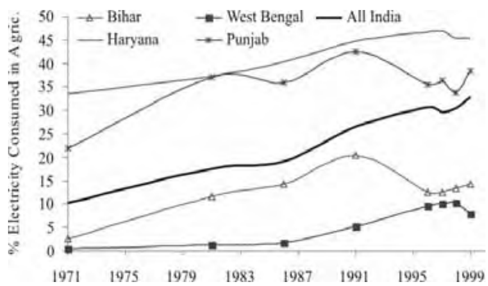

Figure 5. Growth of electricity consumption in agriculture

Simple Measures for Improving Pumping Efficiency

Efficiency of pumping units plays an important role in adoption of pumps and its utilization for groundwater development. A wide variety of pumps are available in the market. However, cheaper pumps are mostly low priced, but are of low efficiency. Low efficiency of pumping units is also responsible for excessive energy consumption, reduced irrigation efficiency and low productivity but, due to lack of knowledge and considering the subsidy in the electricity, most of the farmers prefer to go for cheaper pumps. These pumps give poor discharge even with higher horse power (hp) capacity pumps. It is, therefore, important that awareness is created about use of efficient pumps. This requires knowledge about the parameters to be considered for selection of pumps and, how the efficiency of the pumps can be enhanced.

The energy consumption depends mainly on pump discharge, height of water lift, time of operation and efficiency of pumpset (pumps, drive and motor/

engine, and their installation). If certain rectification measures are carried out for improving the efficiency of pumping unit then the potential energy saving (PES) in percent may be worked out as

$$PES = 100\left[1 - \frac{Y_2}{Y_1}\frac{\eta_1}{\eta_2}\frac{R_1}{R_2}\frac{H_2}{H_1}\right] \qquad \ldots(1)$$

The subscript 1 and 2 refer to the values before and after the rectification. Hence, to save energy efforts are required to:

i) improve the performance rating R (ratio of amount of fuel theoretically used by the pump to actually used) such that $R_2 > R_1$;
ii) reduce the water lift head H ($H_2 < H_1$);
iii) reduce depth of irrigation Y ($Y_2 < Y_1$); and
iv) increase irrigation efficiency (η).

In order to improve the performance rating, pump efficiency standards need the substantial improvement and enforcement to discourage substandard pumps being sold in market. The efficiency standards should also consider allowance for the effect of deterioration in pump efficiency with time and anticipated unfavorable conditions such as higher suction lift, and poor quality water (Sant and Dixit, 1996). Development of energy efficient components of pumping unit under the prevailing conditions of the farmers' field, development of well designs, and construction methodology with minimum losses and less chances of failures, are the challenges for the research and developmental units of government and industrial agencies.

From a user point of view, after selection of pump, it is important that it is installed properly with correct fittings and accessories, and appropriate suction lift. However, the suction lift varies with changing water table in the field conditions. Under aegis of AICRP on "Optimisation of Ground Water Utilisation through Wells and Pumps", several studies have been conducted to investigate the reasons for lower efficiencies of the pumps at different locations in India. The major reasons for low efficiency of pumps, as identified in these studies are listed in Box 1.

Box 1. Major reasons for low efficiency of pumps.

- Mismatch of selected units with the well conditions.
- Mismatch of the drive units with the pump requirement.
- Excessive length of delivery pipe.
- Excessive suction lift.
- Use of inefficient foot valves (offer very high head loss).
- Use of reducer at the delivery side (use of 10 x 8 cm nipple at the outlet of delivery pipe of 10 cm diameter pump).
- Poor quality of pipe fittings with unnecessary short radius bends.
- Loose foundation causing excessive vibrations during operation.
- Lack of technical service and awareness to the farmers on purchase, selection, installation and operation of pumps.

The efficiency of the tested pumps from field installations, were found to vary depending upon the make of the pump, its installation and fittings, and operating conditions (Fig. 6).

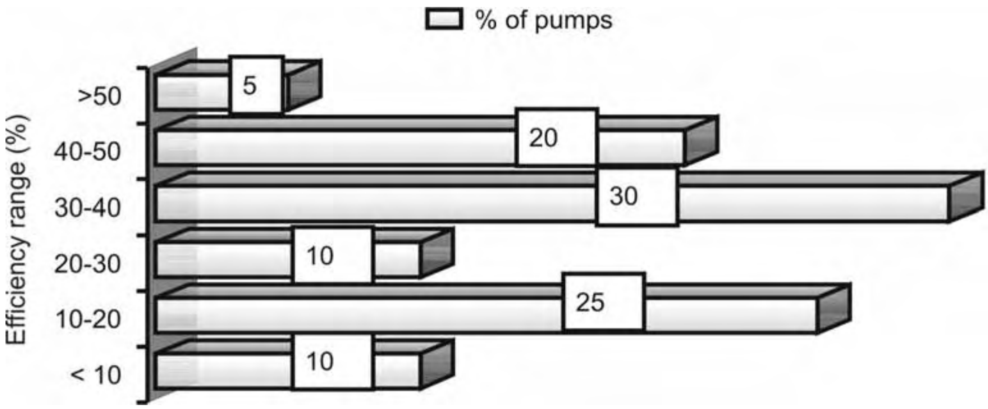

Figure 6. Proportion of pumps under different efficiency range

More than 35% of pumps were found to have efficiency less than 20%. All the low performing pumps were found to have problem either with their fittings, poor condition of foot valve, improper installation and suction lift. These pumps were found to respond substantially to small rectification measures in terms of increased discharge as well as efficiency (Table 1).

Table 1. Comparative performance of pumping units before and after rectification (Jabalpur, 1998)

Make	Year*	HP	Discharge, L/s			Efficiency, %			Rectification Measures*			
			Before	After	%	Before	After	%	S	F	L	FT
I	1989	5	6.35	8.15	28.3	21.95	28.01	27.6	-	Y	Y	Y
II	1993	5	7.00	11.80	68.6	24.50	41.4	69.0	1.70	-	Y	Y
III	1991	5	5.50	8.60	56.4	17.14	26.81	56.4	0.40	Y	Y	Y
IV	1996	5	7.00	8.60	22.9	18.20	23.42	28.7	-	Y	Y	Y
V	1992	5	5.00	7.10	42.0	24.21	34.38	42.0	1.20	Y	Y	Y
VI	1996	5	8.00	9.85	23.1	20.30	25.32	24.7	-	-	Y	Y
VII	1987	5	3.60	5.25	45.8	10.54	15.37	45.8	-	Y	Y	Y
VIII	1990	5	4.50	7.30	62.2	8.71	14.23	63.4	0.90	Y	Y	Y
IX	1992	5	6.00	8.65	44.2	16.88	24.34	44.2	1.00	Y	Y	Y
X	1996	7.5	11.50	14.96	30.0	18.40	23.28	26.5	-	Y	Y	Y
Average			6.45	9.03	40.0	18.08	25.66	41.9				

S – Suction head reduced (m); F – Foundation improved; L – Leakage stopped; FT – Excessive fitting removed. *Year of installation

In another study, rectification measures were carried out on 14 pumps owned by farmers in the *Tarai* region of Pant Nagar with respect to removal of nipple at the delivery side and replacement of short radius bends with long radius bends. These rectifications resulted in increase of discharge rate (on an average by 4.83%) of the pumps and saving in the fuel consumption of about 190 liter/year.

Apart from these fittings and installation, use of good quality foot valve is also an important factor for efficiency improvement. Results of rectification carried out on 241 pumps in 24 villages by GBPUAT, Pantnagar in *tarai* area, clearly indicated that improved foot valve saved about 11% energy (Table 2).

Table 2. Effect of foot valve and pipe fittings on discharge and power consumption

Fittings on Suction	Pipe fittings on delivery side							
	Elbow		Short radius bend		Standard bend		Total	
	Discharge (lps)	Power (watts/ lps)	Discharge (lps)	Power (watts/ lps)	Discharge (lps)	Power (watts/ lps)	Discharge (lps)	Power (watts/ lps)
With Local Foot Valve								
Elbow	26.80	181.45	28.88	173.71	25.39	162.47	27.02	172.54
Short radius bend	25.03	181.72	28.99	170.42	27.56	163.32	27.19	171.82
Standard bend	27.60	171.68	27.38	169.14	29.26	160.45	28.08	167.09
Average	26.48	178.28	28.42	171.09	27.40	162.08	27.43	170.48
With Pantnagar Foot Valve								
Elbow	40.28	156.38	40.37	156.82	41.41	149.70	40.69	154.30
Short radius bend	41.27	156.36	40.80	156.90	41.74	148.01	41.27	153.76
Standard bend	41.91	150.16	43.43	156.22	44.02	140.93	43.12	149.10
Average	41.15	154.30	41.53	156.65	42.39	146.21	41.69	152.39
Overall Average	*33.82*	*166.29*	*34.98*	*163.87*	*34.90*	*154.15*	*34.56*	*161.44*

Note: lps: liters per second

Based on the testing of 20,000 pumps owned and operated by farmers and rectification measures of one type or another carried out on 10,000 pumps, ICM, Ahemedabad prepared the recommendations for potential energy saving from different measures as given in Fig. 7.

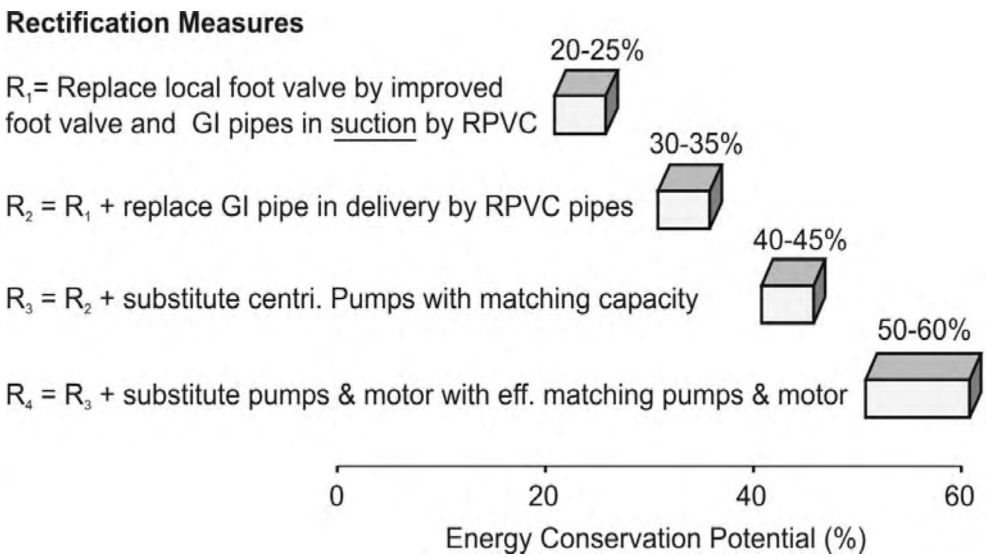

Figure 7. Effect of different rectification measures on energy conservation

The performance of pumps in the EIGP is also very poor, but detailed study in this respect is required to be carried out. There is a vast scope to adopt above such measures to improve pumping efficiency in eastern region.

Efficient Water Management for Enhancing Productivity of Pumped Water

Since most of the pumps in EIGP are operated by diesel, ground water becomes too costly for the farmers to irrigate their fields. Farmers are therefore interested in saving water along with maximizing its benefit, or in other words enhancing water productivity. Water management therefore becomes an important issue for ground water users. Agricultural water management is an important aspect influencing the overall groundwater draft and energy requirement. Broadly, the important water management measures for enhancing productivity of groundwater in EIGP would involve (a) proper irrigation scheduling, (b) improved agronomic practices, (c) conjunctive use of rain, canal and groundwater, (d) optimization of rice transplanting date, (e) acceleration of resource conserving technologies such as zero tillage, conservation tillage and raised bed, (f) use of water and energy efficient irrigation methods, for example micro-irrigation, and (g) multiple water use. Under the aegis of AICRP on Water Management, the optimum schedule of irrigation has been worked out for most of the important crops grown in different agro-climatic zones of the country. By adopting these recommendations, substantial amount of water can be saved and the yields can be increased. As it is perceived that rice needs continuous submergence, but studies undertaken all over the country revealed that the intermittent irrigation as impounding of 5±2 cm of water in the rice fields three days after disappearance of previously ponded water is the most optimum irrigation schedule. The results indicated that such treatment could save 23 to 65% of water as compared to traditionally rice growing under continuous submerged condition.

The methods of water application play an important role in controlling the water losses through deep percolation, surface runoff, and direct evaporation from soil surface. Among the gravity fed irrigation systems, border irrigation is mostly recommended for cereals except paddy for which check basin irrigation is traditionally used. Furrow irrigation with its different configurations saves appreciable water over the other methods. However, all the gravity methods need to be adopted with utmost care and recommended design parameters, so that the irrigation efficiency can be achieved to the maximum extent. Pressurized irrigation system (drip, sprinklers, and micro-sprinklers) are efficient irrigation methods. The water saving varies in the order of 20-30% with the sprinklers. Drip irrigation saves large amount of water (40-60%) as compared to gravity methods and makes appreciable improvement in quantity and quality of produce. Low cost star microtube drip irrigation method (newly developed and refined) has been tested and found beneficial for banana and vegetable crop in farmer's field condition of south Bihar (Bhatnagar, 2005). Even without considering the benefits of water saving, the benefit cost ratio worked out for the system was 1.18 to 1.24 depending upon the variety and crop spacing used. The energy requirement for pumping water from varying groundwater depths (3, 7, 11 and 15m) for surface (gravity) and drip irrigation was analyzed at WTCER, Bhubaneswar (Srivastava and Upadhyaya, 1998). The results show that the energy requirement gets reduced substantially with drip irrigation as compared to gravity irrigation system (Fig.8).

Technological Push for Groundwater Utilization

Some of the reasons for underutilization of groundwater in realizing the potential are understood to be medium to high rainfall, canal water supplies, small and highly fragmented land holdings, poor economic condition, lack of access to capital and energy infrastructure, unavailability of smaller and portable diesel pumping units, and unreliable/ energy supplies.

There are examples and evidences to suggest that even with these limitations, awareness regarding the benefits of appropriate agricultural technologies and institutional arrangements have prompted farmers to go for groundwater irrigation and/or conjunctive use of groundwater. Such innovative and cost-effective technologies aimed at value addition and increasing water productivity may provide "technological push" for increased adoption of pumps for groundwater utilization. Such agricultural and water use management technologies when demonstrated in a participatory mode may encourage this push. For example, ICAR-RCER under ICAR-DfID Project demonstrated that accelerating adoption of optimization of rice transplanting through various means of communication not only improved rice-wheat productivity but also encouraged groundwater utilization in the commands of RP Channel-V of Sone Command in Patna. This involved advancing the date of rice transplanting by 15-20 days by raising nursery in the last week of May to first week of June using pumped water and transplanting it in the last week of June to middle of July. Seeing benefit of this techniques, the farmers not only employed use of pumped ground water to raise nursery but also enhanced rainwater utilization, saved irrigation to rice crop, encouraged ground water utilization, timely sowing of wheat and enhanced rice and wheat yields. Timely raising of rice nursery using tube well water, registered 2.5 times increase in groundwater market. Additionally the economics and risks of failure of monsoon/ or canal water supplies which encourage (or discourage) use of groundwater in canal commands and helps in determining the options of purchasing water, renting pumps or having own tube wells. Routing of pumped water for irrigation through a reservoir or tank to enhance water productivity through multiple use and integrating with horticulture, fishery and livestock is another example of

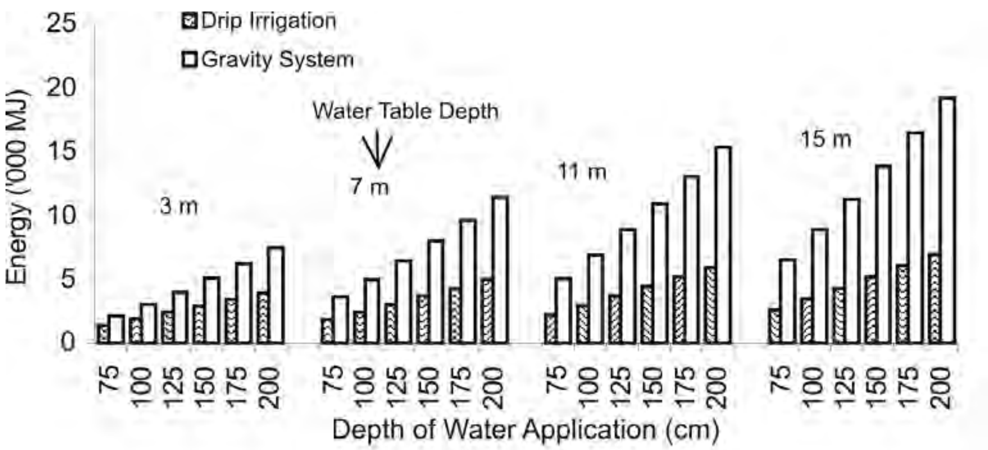

Figure 8. Energy requirement in drip and gravity irrigation

technological push to encourage groundwater utilization for improving water productivity in the eastern region.

In a study, at ICAR-RCER, Patna routing of tube well water from secondary reservoir gave additional benefit in terms of fish harvest of 11.0 tonnes/ha when weekly water exchange was done (Bhatnagar et al., 2004b). There is a need to develop and demonstrate such technologies to provide a technological push and convince farmers in the eastern region for increased adoption of pumps to enhance agricultural productivity.

Group Tubewells – A Cooperative Movement for Enhancing Productivity

There are evidences to support the concept and functioning of group tubewells owned and operated by small and marginal farmers in regions of eastern UP (Deoria) and north Bihar (Vaishali). Group tubewells were installed initially with the initiatives and support of People's Action for Development India (PADI)[1].

Vaishali Area Small Farmers' Association (VASFA), a registered NGO established in 1979, facilitated group borings and tubewells in Vaishali district. They installed 35 group tubewells with 6" or 4" delivery (7.5 – 10 hp pump) with command area of 20 to 40 acres. Each group tubewell has Small Farmers' Association (SFA) with 20 to 40 farmers having nominal membership fee (Rs. 3/month) as service charge, each consisting of a sub-committee of three (a President, Secretary and Treasurer). Each SFA is represented by their President in the Executive Body of VASFA. Water distribution, operation and maintenance are managed by SFA with the help of VASFA. Cost of water includes - operating charges and service charges - as decided by the committee. At present the committee charges Rs. 40/hour from the members and Rs. 50-60/hour from the non-members. Each group tubewell sells around 20% of water to non-members. Conflicts, if any, are being resolved amicably in the meetings. Farmers of tube well commands reported rice and wheat yields of 5-6 ton/ha. Associations also helped the small farmers in meeting their requirements of quality inputs, technology and sale of output at reasonable price besides managing valuable water resource. It demonstrates a good example of PIM in groundwater management, even in "socially disturbed" area.

It has demonstrated a good example of participatory groundwater management through efficient use of tubewell and pump technology to enhance productivity of their fields. When integrated and supplemented with improved resource conservation technology and on-farm water management practices, this could further realize the potential of pump revolution for enhancing water productivity.

Pumps and Groundwater Markets

Advent of low cost pump technology and tubewell technology has led to spontaneous growth of groundwater markets for irrigation in many parts of IG Plains in India and Bangladesh. It involves localized informal sale and purchase of

[1]PADI was the predecessor of Council for Advancement of People's Action and Rural Technology (CAPART).

pumped water mostly through private owned shallow tubewells and low lift pumps. With the expansion of water markets in the private sector, the pricing system has also been undergoing changes to suit the needs of farmers. Groundwater markets have helped small and marginal farmers with small and scattered land holdings in providing access to groundwater for irrigation and enhancing productivity in the eastern region of UP, North Bihar, West Bengal and Bangladesh. Even today, the ownership of mechanical water extraction devices remains out of reach of the marginal farmers in parts of EIGP. In such a scenario, study has shown that the small farmers with land holdings up to 0.4 ha in eastern UP are the biggest beneficiaries of the groundwater market assumes an immense significance (Pant 2004). Our experience with the DfID Project in the commands of RP Channel V in Sone Command at Patna also confirms that small and marginal farmers are greatly benefited through these groundwater markets to access groundwater for irrigating their fields.

Field level institutions for water feel that water markets can help improve water allocation and its use and produce substantial gains for the sellers and buyers. At the same time, there is concern expressed by many others that water markets aggravate equities in rural areas, as it leads to monopoly of rich farmers and their control over the market. Simultaneously, this may also result in excessive exploitation and depletion of scarce resource. Houssain (1996) reports that in real terms, irrigation water has become substantially cheaper after liberalization of the water markets in Bangladesh. At the same time, the ability to sell provides an incentive for conserving water and using it more rationally. Informal water markets in South Asia operating without government interventions are able to increase access to water for some of the poorest farmers (Meinzen-Dick and Sullens, 1994). In Bangladesh, hourly charges have provided incentives to adopt supplementary irrigation in time of drought and have encouraged cultivation of modern varieties in the wet season. However, there are no clear policy statements or legal measures regarding water markets in India. There are arguments for and against water markets, but there can be no difference of opinion on the question of their sustainability. This is a serious issue in water scarce areas since, as depletion proceeds fast, the ecology of area deteriorates and the poor and marginal farmers suffer most. The basic issue, therefore, is that of evaluating a legally and institutionally enforceable system, which will ensure sustainability and provide the parameters within which water markets could operate in the IGB.

Conclusions

- Adoption of low cost pump technology has been rather uneven in EIGP, it is now picking up in different parts of the region such as Bihar.
- It is demonstrated that low cost pump technology has increased the access of marginal and poor and disadvantaged people to groundwater for irrigation either through owing the one, or renting the pumps or purchasing water through groundwater markets in EIGP.
- Low cost pump technology is increasing water productivity and livelihood not only in poor regions but also among poor farmers of EIGP-a pro-poor policy.

- Need to evolve and demonstrate innovative and cost effective technologies aimed at value addition through multiple uses and increasing water productivity to provide "Technological Push" for accelerating adoption and efficient utilization of pumps for groundwater utilization.
- Challenges for the research and development include development of energy efficient pumping units, low cost small capacity diesel pump sets, promoting participatory on-farm water management practices, multiple water use interventions, cooperative movement in groundwater utilization and management, and research on institutional, legal and policy issues relating to groundwater development and water markets.

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Using Recharge Estimation by the Water Balance Method as a Baseline for Sustainable Groundwater Management in a Water-Scarce Region of Syria

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Abstract

During the period of observation, groundwater abstractions by farmers in Khanasser valley, a water-scarce region of northwest Syria were largely sustainable. This was found by using the water balance method during a period of near average rainfall. As water levels were hardly changing, it was assumed that groundwater abstractions were in balance with net recharge. Agricultural water-use was assessed by monitoring abstractions on 20% of the irrigated area. Total groundwater abstractions in agriculture were estimated by extrapolating the average water-use per crop and irrigation method to the entire mapped irrigated area. Agriculture accounted for about 75% of groundwater abstractions. Domestic water-use was added onto this and the recharge value was estimated at around 2.5% of the average annual rainfall of 210 mm by dividing total groundwater abstractions by the surface area of the two watersheds.

In the past, water levels were dropping due to cotton irrigation in the summer. Although cotton has meanwhile been prohibited in this region by government decree, the danger of overusing groundwater resources still persists due to a gradual expansion of the irrigated area. The farmers should be made aware to maintain the status quo and not to apply more than an average of about 1500 cubic meters per hectare. Water in agriculture is currently used for supplemental irrigation of wheat (60%), barley (17.5%) and cumin (4.5%) from October to May. The rest (18%) is applied in summer, mainly to vegetables and olives. Irrigated crops are compared with regard to water management and income.

Introduction

In many parts of Syria, excessive pumping has caused lowering of the water table with negative effects on the irrigation economy due to higher energy and investment costs. The Syrian Government has ratified legislation to safeguard water resources and to stop or possibly reverse the depletion of aquifers. Cabinet Decision 11 of 5/ 7/ 2000 was issued at a national level to replace the traditional irrigation techniques with pressurized irrigation systems within four years and to support farmers with low interest loans for this purpose. Agricultural credit for purchasing new irrigation equipment was made available also for Zone 4, provided well owners had a valid license. Zone 4 receives 200-250 mm annual rainfall and equals about 10% of Syria's land surface.

The Khanasser Valley (Figure1) is located in Zone 4, approximately 80 km southeast of Aleppo. It stretches 20 km between the Jabboul salt lake in the north and the border of the Syrian steppe near Adami village in the south. Basalt plateaus of the tertiary age border the valley in the east and west. The annual average long-term rainfall in Khanasser Valley is 209 mm with about 53 % probability (Bruggeman 2004). The deep calcareous soils in the valley have a silt loam to clay loam texture and basic infiltration rates of around 50 cm/day (Schweers et al. 2004(a). Rearing sheep is the most important source of agricultural income and land-use is dominated by the barley-livestock system. Irrigation is used only on about 4% of the cropped area. Most of the irrigation wells had been installed in the early nineties. As a result of a "well boom", the groundwater tables had dropped. At least, this was indicated by a comparison of a few wells with earlier records (Schweers et al. 2003). In 1998, irrigation of cotton from groundwater in Zone 4 was prohibited. Since then the area planted with olives has expanded and cumin was introduced as a cash crop.

Figure 1. Overview of northwest Syria with Khanasser Valley

The quantification of recharge as a criterion of sustainable groundwater abstractions in dry areas is difficult. Due to accuracy limits, values below 2% cannot be determined even with advanced isotope methods (Geyh 2003). Mathematical groundwater models are useful, but only good at representing complex realities if accurate input data are available. To collect such data is often beyond the scope of institutions in developing countries. Simple box models may be used as a substitute for more refined approaches. A box model is based on a simplified concept of the aquifer as a container which receives and looses water in the form of vertical recharge, groundwater abstractions, return flows, evaporation from the aquifer, groundwater inflows and outflows, water imports and exports. The changes in the water table are related to the balance of these processes and aquifer storage, i.e. the higher the storage, the less sensitive the water table reacts to changes in aquifer volume. Inflows, outflows and recharge can be grouped together as "net recharge". In case the balance of imports and exports (i.e. piped delivery of drinking water – transport of groundwater out of the watershed) and evaporation from the aquifer within the domain of the model are not significant, net recharge is in balance with net groundwater withdrawal and the change in storage:

$$R_{net} = Q_{net} \pm dS \qquad \text{(Equation 1)}$$

where:

R_{net} = net recharge (inflow-outflow+recharge)

Q_{net} = net groundwater withdrawal (abstractions-return flows)

dS = (±) change of storage in the unconfined aquifer of the watershed.

The change in storage equals the change in the average water level multiplied by the storage coefficient. For example, if an aquifer of 100-km^3 extent has 0.5% storage and the water level drops by 20 cm, it looses 100,000 m^3 (1,000,000 m^3/km^3, 100 km^3 x 0.005 x 0.2 m/m). Aquifer geometries can be determined from information on the stratification of wells or geoelectrical investigations. The storage coefficient can be computed from pumping test results. If the storage is not known for lack of reliable data, net recharge can still be approximated from well-determined groundwater abstractions if the groundwater table happens to remain at the same level over the period, i.e. if there is practically no change in storage. This method will produce an average recharge value under the condition that the average rainfall during the period of observation is near the long-term average.

Materials and Methods

Rainfall was recorded from automatic weather stations. Pumping tests were made in thirteen wells and evaluated with the Jacob-Cooper and the Theiss recovery method (Krusemann and Ridder, 1970). Irrigated areas were mapped using a GPS. Agricultural groundwater abstractions were assessed by irrigation monitoring during two consecutive seasons and the resulting average abstraction volumes of the monitored areas were extrapolated to all mapped areas with the same crops and irrigation methods (Schweers at al 2004(b). Since rainfall during the monitored seasons of 2002/03 and 2003/04 was above average, a fictitious dry year with 30% higher abstractions than the average of the monitored seasons was added to estimate long-term abstraction averages for winter crops. In the case of summer crops, the findings during the monitored seasons were considered representative. Groundwater abstractions from the cretaceous aquifer were taken as 50% effective for the water balance of the first aquifer. This was based on the observation, that the deep wells need to be pumped for about two days until the water is purely cretaceous (most deep boreholes are not lined).

Domestic water use assessment was based on average abstractions per capita and per head of livestock. Population figures were taken from Mazid and Al Hassan (2002). The operator of the distribution point at Rasm Anafl in the northern part of the valley gave information on the import of Euphrates water. Export volumes to the steppe basin were estimated from observations of an elder who had observed the movement of vehicles with water containers out of the Hobs-Harbaqiye valley, a side valley of the southern watershed with low-salinity water. Agronomic and economic data were raised during interviews with farmers.

Economic data were collected through interviews in consultation with the NRMP socio-economists to get base data for the calculation of crop budgets. The rainfed net income was subtracted from the net income derived by irrigating the same crop. The differential net income (irrigated-rainfed) was then divided by the amount of abstracted groundwater to show the average incremental income per unit of water resource. Family labour, whether paid or unpaid was not accounted as a real cost. Rather, the differential net income was divided by the total family labour hours spent with the irrigated crop (including irrigation hours) to show how much extra income per hour was generated as a result of irrigation.

Results

Sustainable Groundwater Abstractions

The alluvial quaternary aquifer was mostly confined or semi-confined, with low storage (Table 1), which indicated that the water level reacted easily to changes in aquifer volume. A storage coefficient for the limestone aquifer (Paleogene) could not be determined, because in a fractured aquifer, the reaction of observation wells depends on the chance that they are situated on a fracture. Mostly, there was no reaction of observation wells, even if they were quite close to the main well. The fact, that most Paleogene wells were not very productive and that farmers used *Arabic wells* with large storage receiving water from horizontal borings of several hundred meters lengths (Hoogeveen and Zöbisch 1999), illustrated a comparatively small dimension of specific storage in the unconfined aquifer of maybe as low as $2 \cdot 10^{-2}$ m^{-1} (≈ 2%) or even lower.

Table 1. Average aquifer characteristics derived from pumping tests

Aquifer	Trans-missivity (m²/day)	Hydraulic conductivity (m/day)	Storage coefficient	Specific storage coefficient (m-1)
Quaternary	86.7	17.8	2.6E-03	3.2E-04
Paleogene	2.9	0.07	-	-

Rainfall during the period of observation was near the long-term average (Fig.2). Despite seasonal fluctuations, the water level over the entire period remained more or less constant (Fig.3). Based on the monitoring results in the 2002-04 seasons and an estimate of 30% higher water-use for a dry year (Table 2), the following rounded average water-use was computed for winter crops: 140 mm

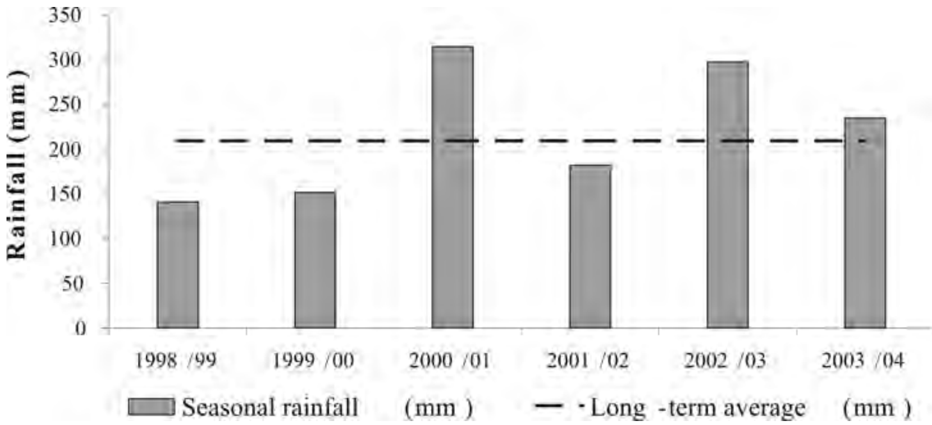

Figure 2. Seasonal rainfalls during the period of observation

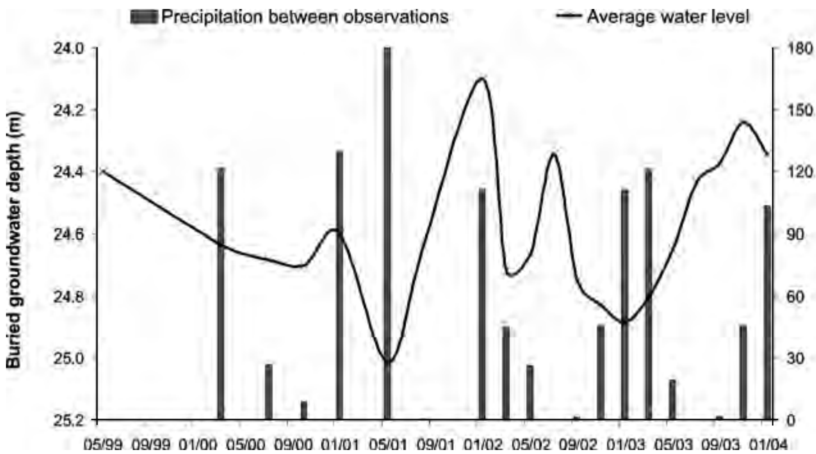

Figure 3. Fluctuations of the water level in response to precipitation

Table 2. Monitored area and water use of winter crops

Crop		Barley		Cumin	Wheat	
Irrigation method		Sprinkler	Surface	Sprinkler	Sprinkler	Surface
Monitored fields		9	5	5	12	7
Monitored area (ha)		26.8	6.8	7.8	37.5	14.6
Water-use (mm)	2002-03	95	145	27	105	327
	2003-04	134	215	84	146	320
	Dry year*	150	234	73	163	421
	Average	126	198	61	138	356

Note: *estimate (monitored average + 30%)

(wheat-sprinkler), 360 mm (wheat-surface), 130 mm (barley-sprinkler), 200 mm (barley-surface) and 60 mm (cumin-sprinkler). Under this scenario, an estimated 790,000 m^3 (82%) are abstracted for supplementary irrigation of wheat (60%), barley (17.5%) and cumin (4.5%) and 176,000 (18%) for summer crops (Table 3).

Table 6. Average agronomic data of monitored farms in 2002-04 (winter crops)

Parameters	Barley-sprinkler	Barley-surface	Barley-rainfed	Cumin-sprinkler	Cumin-rainfed	Wheat-sprinkler	Wheat-surface	Wheat-rainfed
No. of monitored fields	9	5	12	5	4	12	7	11
Monitored area,(ha)	26.8	6.8	71.7	7.8	22.5	37.5	14.6	39.2
Dominant Variety	Arabi aswad	Arabi aswad	Arabi aswad	Local	Local	Cham 6	Cham 6	Cham 6
Planting date	01/11/02	28/10/002	25/11/002	31/12/02	30/12/02	26/11/02	29/11/02	21/11/02
Harvesting date	16/05/03	14/05/03	15/05/03	15/05/03	17/05/03	26/05/03	27/05/03	27/05/03
Growing period (days)	196	198	171	135	138	181	181	187
Seed rate (kg/ha)	237	310	146	37	34	241	321	153
Yield 2002-03 (kg/ha)	2174	2762	1959	500	471	3175	3472	1856
Yield 2003-04 (kg/ha)	1464	1834	928	522	511	1696	3445	1162
Yield average (kg/ha)	1819	2298	1444	511	491	2436	3459	1509

Table 7. Average water use data of monitored farms in 2002-04 (winter crops)

Parameters	Season	Barley-sprinkler	Barley-surface	Cumin-sprinkler	Wheat-sprinkler	Wheat-surface
EC of irrigation water (dS/m)	2002-03	7.2	11.7	4.9	5.8	10
EC values (min-max)	2002-03	3.3-14.2	8.4-16.8	2.5-7.9	2.3-11.4	3.3-14.2
Crop water requirements (mm)	2002-03	372	372	259	390	390
	2003-04	379	379	269	423	423
	Average	376	376	264	407	407
Effective rain (mm)	2002-03	284	284	228	268	268
	2003-04	218	218	177	209	209
	Average	251	251	203	239	239
Net irrigation requirement (mm)	2002-03	88	88	31	122	122
	2003-04	161	161	92	214	214
	Average	125	125	62	168	168
Water-use (mm)	2002-03	95	145	27	105	327
	2003-04	134	215	84	146	320
	Average	115	180	56	125	324
Factor water-use/ Irrigation requirement	2002-03	1.1	1.6	0.9	0.9	2.7
	2003-04	0.8	1.3	0.9	0.7	1.5
	Average	1.0	1.5	0.9	0.8	2.1
WUE_{rf} (kg/ha·mm)	2002-03	9.0	9.0	2.1	6.9	6.9
	2003-04	4.3	4.3	2.9	5.6	5.6
	Average	6.6	6.6	2.5	6.2	6.2
WUE_{tot} (kg/ha·mm)	2002-03	5.7	6.5	2.0	8.5	5.8
	2003-04	4.2	4.2	2.0	4.8	6.5
	Average	4.9	5.4	2.0	6.6	6.2
WUE_{ir} (kg/ha·mm)	2002-03	2.1	5.7	1.1	12.1	5.2
	2003-04	4.0	4.2	0.1	3.7	7.1
	Average	3.0	5.0	6.0	7.9	6.2

Table 3. Agricultural groundwater abstractions

Crops		Irrigation method	Average water use (m^3/ha)	Northern watershed		Southern watershed		Total area			
				Area (ha)	WU@ (m^3)	Area (ha)	WU (m^3)	Area (ha)	WU (m^3)	Area (ha)	WU (m^3)
Winter crops	Wheat	sp*	1400	77.9	109060	143.7	201180	221.6	37.0	310240	32.2
	Wheat	su**	3600	26.2	94320	53.9	194040	80.1	13.4	288360	29.9
	Reflowwh (8%)	su	-288		-7546		-15523			-23069	-2.4
	Barley	sp	1300	38.8	50440	50.5	65650	89.3	14.9	116090	12.0
	Barley	su	2000	7.1	14200	21.2	42400	28.3	4.7	56600	5.9
	Reflowba (4%)	su	-80		-568		-1696			-2264	-0.2
	Cumin	sp	600	21.8	13080	46.7	28020	68.5	11.4	41100	4.3
	Others (e.g. lentils)	sp	800	1.6	1280	0.1	80	1.7	0.3	1360	0.1
	Total/areal average		1611	173.0	274266	316.0	51451	490.0	81.7	788417	81.7
Summer crops	Vegetables	su	3300	2.5	8339	6.0	19800	8.5	1.4	28139.1	2.9
	Vegetables	dr***	4500	1.0	4500	2.8	12600	3.8	0.6	17100	1.8
	Cotton	su	13500	2.7	36450	5.6	75600	8.3	1.4	112050	11.6
	Olives	su	300	19.8	5940	16.4	4920	36.2	6.0	10860	1.1
	Olives	dr	250	1.4	350	2.3	575	3.7	0.6	925	0.1
	Olives	ta	140	17.3	2422	28.9	4046	46.2	7.7	6468	0.7
	Others (Pistachios)	su	160	2.8	12600	3.0	480	3.0	0.5	480	0.0
	Total/areal average		1600	45.0	58001	65.0	118021	110.0	18.3	176022	18.3
	Total / areal average		1609	218.0	332268	381.0	632172	599.0	100.0	964439	100.0

@WU = Water use, *sp = Sprinkler, **su = Surface basin, ***dr = Drip

In contrast to the situation in 1998/99 (Hoogeveen and Zöbisch 1999) when sprinkler irrigation was exceptional, during the period of 2002-2004, sprinklers were used on 64% of the irrigated area and delivered 49% of the total irrigation water (Fig.4). The rest was mainly basin irrigation. Return flow from surface irrigation was roughly estimated at 8% (wheat) and 4% (barley).

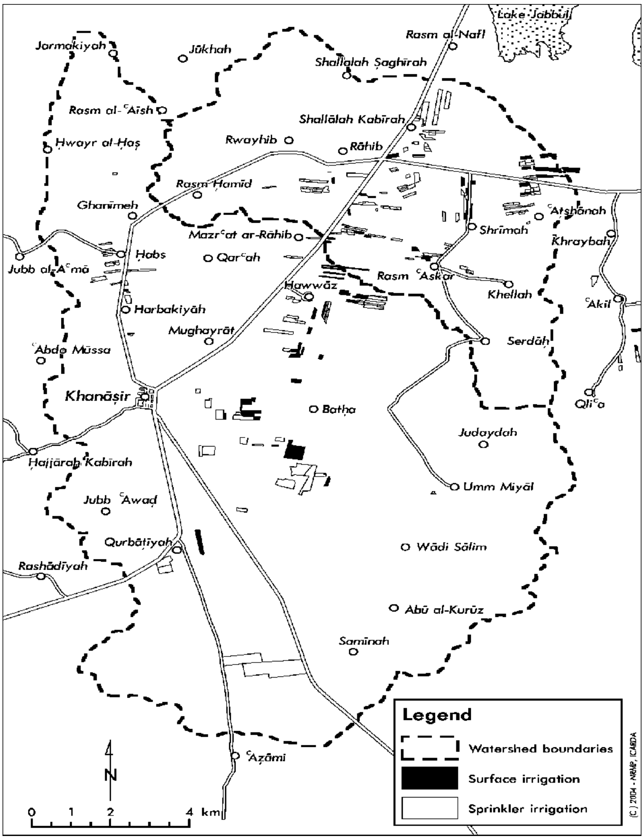

Figure 4. Khanasser Valley, 2002-03 cropping season: Fields irrigated by sprinkler irrigation and surface irrigation (from Schweers et al. 2004(b)

Net water import into Khanasser valley amounted to 30,000 cubic meters or 10% of total domestic abstractions (Table 4). The domestic water-use per capita was approximately 54 litres per day (l/day), 10 litres more than the middle-east average (FAO 2004). According to the estimate, total drinking water consumption reached 100,000 litres. Local and migrant sheep consumed nearly as much water as the inhabitants of the valley. The remainder, about 50% of the total was used for cleaning, washing, and the irrigation of vegetables in home gardens.

Under the condition, that during a period of average rainfall groundwater abstractions were largely in balance with recharge, the net recharge estimate (+/-20%) ranged from 1.9% to 2.9% of the long-term seasonal average (Table 5). For an irrigated area of 600 ha, this results, in an average equivalent abstraction of 160 mm/ha.

Table 4. Domestic groundwater abstractions

Domestic water-use		Estimated per-capita consumption (m^3/day)	No. of days	No. of residents		Water use (m^3/yr)		
				North	South	North	South	Total
Drinking water, sanitation	Residents	0.020	365	5475	5775	39968	42158	82125
	Migrants	0.020	240	1825	1925	8760	9240	18000
	Total	-	-	7300	7700	48728	51398	100125
	Water import	-	-	-	-	30000	20000	50000
	Effective	-	-	-	-	18728	31398	50125
Livestock	Residents	0.005	365	12000	28000	21900	51100	73000
	Migrants	0.005	90	6000	14000	2700	6300	9000
	Total			18000	42000	24600	57400	82000
Other	Cleaning, Washing, Gardens	-	-	-	-	60909	89946	150855
	Water export	-	-	-	-	-	21000	21000
Total domestic	-	-	-	-	-	104237	199743	303980

Table 5. Total water-use and recharge estimates

	North		South		Total	
	m^3	%	m^3	%	m^3	%
Agricultural water use	332268	34.5	632172	65.5	964439	76.0
Domestic water use	104237	34.3	199743	65.7	303980	24.0
Total water use	436504	34.6	831915	65.4	1268419	100.0
Watershed area (ha)	7640	30.3	17610	69.7	25250	100.0
Water use (mm)	5.7		4.7		5.0	
Average rainfall (mm)	209		209		209	
Net recharge (%)	2.7		2.2		2.4	
NR x 0.8 (%)	2.2		1.8		1.9	
NR x 1.2 (%)	3.3		2.7		2.9	

Agricultural Water Management

Seed rates of wheat and barley (Table 6) were found to be higher than recommended by the Ministry of Agriculture (Haddad 2004). To explain the difference, some farmers mentioned bird damage and claimed to have better results with higher seed rates. Irrigated yields in the monitored seasons were more representative of average conditions than rainfed yields, which were higher due to good rainfall in the 2002-03 season. Rainfed wheat yields in 2003-04 were also comparatively good.

The salinity of the irrigation water applied to winter crops was highest for barley, lower for wheat and lowest for cumin (Schweers et al. 2004(a). More saline water was used preferably with surface irrigation methods. On average, about one third more water was applied to winter crops than needed to satisfy the crop water requirements (Table 7). In this context, the irrigation water-use efficiency is defined as the differential yield (to rainfed yield) in kg per ha·millimetre of abstracted irrigation water. For sprinkler-irrigated wheat (7.9 kg/mm), it was higher than the rainwater use efficiency (6.2 kg/mm). In the wet 2002-03 seasons, supplemental sprinkler irrigation achieved the best water productivity (12.1 kg/mm). In the following season with just above average rainfall and a long dry period in spring, surface irrigation was more productive.

Physical water-use efficiency ratios are meaningful to compare yields within one crop or between irrigation methods, whereas the economic efficiency of water resources can better support decisions of choice. Table 8 shows an economic comparison of irrigated crops grown in Khanasser valley: Grazing lambs in early spring increases the profitability of sprinkler-irrigated barley. According to Pape-Christiansen (2001), 144 kg life weight gain during 6 weeks of grazing produce 13,700 SL (Syrian Lira) gross incomes. In return to labour input, wheat turned out to be the most profitable crop. Irrigation of cumin at low application rates yielded 14 SL per ha·mm. The economic water use efficiency (net income/ irrigation) of summer crops was higher than that of winter crops, which derive only an incremental income (to the rainfed income) from irrigation. The profitability per land unit was highest in the case of irrigated vegetables. Olives achieved the best irrigation benefit.

Discussion

Sustainable Groundwater Abstractions

During a trial with surface-irrigated wheat in the 2003/04 seasons, the soil water balance showed an excess of about 25% of total supplied water (rain + irrigation) over crop evaporation. The average of twelve soil moisture measurement locations was equivalent to 109 mm or 27% of irrigation. It was assumed that most of the drained water, (about two thirds) would be temporarily stored below the root zone (105 cm) in the deep soils and still evaporate from there during the following dry season. The effective return flow would then be approximately 8%. The resulting value is in the range of irrigation return-flow values mentioned by Hobler (2002) for Agricultural Productivity Zone 4.

Farmers of Rahib-Roehib mentioned that they harvest about 30% more on drip-irrigated plots than on surface-irrigated plots. They found, that the amount of water used per unit area had been higher with drip irrigation. Most vegetables, e.g. cucumber have a shorter growth period than cotton, which requires 6-7 months. They are grown successively on adjacent plots, which reduce the irrigation volume per unit area. For cotton, Haj-Dibo (2003) observed irrigation amounts of 8500 m^3 (drip) and 11500 m^3 (furrow) in two fields near Tel Hadya. Hoogeveen et al. (1999) determined an average of 34,000 m^3 in Khanasser Valley. In South-Australia, tomatoes and cotton received similar amounts of water: 5500 – 14,500 m^3 (Thomson 2004). Irrigation of olives was low due to the fact that the average age of plantations in Khanasser was only about 5-6 years. Few farmers used drip-irrigation for olives, like the owner of well No. 89, who filled a reservoir from his well that had enough water for only 1-2 hours/day and irrigated the olives by

Table 8. Water use economy of irrigated crops in Khanasser valley (in SL/ha)

Crop		Winter crops					Summer crops			
		Barley		Cumin	Wheat		Vegetables		Olives	
Irrigation method		Sprinkler	Surface	Sprinkler	Sprinkler	Surface	Drip	Surface	Drip	Surface
Income	Yield (kg/ha)	*1819*	*2298*	*525*	*2436*	*3459*	*45283*	*40250*	*2464*	*1971*
	Income (SL/ha)	12733	16086	25200	25578	36320	259783	196458	73929	59143
	Yield of byproduct, e.g. straw (kg/ha)	*3092*	*3907*	-	*4141*	*5880*	-	-	-	-
	Income from byproduct (SL/ha)	7731	9767	-	10353	14701	-	-	-	-
	Other income, e.g. grazing (SL/ha)	13680	-	-	-	-	-	-	-	-
	Total income	34144	25853	25200	35931	51020	259783	196458	73929	59143
Expenditure (excl. family labour)	Cultivation	800	2000	1488	800	2000	2000	2000	960	960
	Establishment	2296	2880	2716	39534	5034	8367	8667	381	381
	Fertilization	2226	3442	1268	3372	3832	46000	46000	4520	4520
	Crop protection	-	-	1535	950	950	27750	27750	2207	2207
	Irrigation	1656	2500	750	1719	4500	8100	3650	1125	749
	Harvest	2760	4103	3542	4041	6035	20000	20000	24000	24000
	Other operation costs	6840	-	-	-	-	41073	28750	5255	5255
	Capital costs	7060	4180	7060	7060	4180	22210	3000	4180	4180
	Total expenditure	23638	19105	18358	21896	26530	175499	139817	42629	42253
Irrigated net income	10505	6748	6842	14035	24490	84284	56642	31300	16890	
Rainfed	*Grain yield*	*1011*	*1011*	*494*	*951*	*951*	-	-	-	-
	Gross income	11372	11372	23712	14027	14027	-	-	-	-
	Expenditure	4878	4878	17724	6670	6670	-	-	-	-
	Net income	6494	6494	5988	7357	7357	-	-	-	-
Differential income (irrigated - rainfed)	4012	254	853	6678	17133	-	-	-	-	
Water	*Irrigation amount (mm)*	*130*	*200*	*60*	*140*	*360*	*450*	*330*	*90*	*60*
	Net irrigation benefit/cost (SL/mm/ha)	30.9	1.3	14.2	47.7	47.6	187.3	171.6	347.8	281.5
Labour	Irrigation labour (hrs/ha)	88	133	50	92	240	141	219	30	40
	Other family labour (hrs/ha)	126	44	228	48	66	2295	2295	1284	1284
	Total family labour (hrs/ha)	214	177	278	140	306	2436	2514	1314	1324
	Irrigation labour income (SL/hr)	18.7	1.4	3.1	47.7	56.0	34.6	22.5	23.8	12.8

Note: SL= Syrian Lira

gravity. Tubeileh et al. (2004) calculated an irrigation requirement for mature trees in Khanasser valley.

A complete water balance would have to include an outflow component in the form of underground leakage into *sabkhas*, lake Jabboul in the northern watershed and the Karaitch depression (Wolfart 1966) in the southern watershed. In this study, the lower parts of the watershed, where water is too saline for irrigation have not been included in the domain of the water balance (see delineation of watersheds in Figure 4). An outflow component was not considered, as the water levels in the upper part of the basin were reflecting the balance between water use and net recharge (= recharge – outflow).

It must be conceded that there are a number of uncertainties in the water balance, from the accuracy and representativeness of the abstraction assessment to the concept that recharge during the period of observation was in balance with groundwater abstractions. Yet, an average value of 1500-m^3/ha abstractions for an irrigated area of around 600 ha could be taken as a point of departure for delineating sustainable groundwater abstractions. However, further observations should be made to validate the dimension of an average sustainable abstraction value.

Agricultural Water Management

Despite the fact, that on average, the physical water-use efficiency of sprinkler-irrigated wheat was 25% higher than surface-irrigated wheat, for the two observed seasons, the net irrigation benefit per unit of water (SL/ha·mm) and labour (SL/labour hr) was equal for both methods (~50 SL). Moreover, the net irrigation benefit per unit of land was about twice as high in the case of surface irrigation due to higher yields. A categorical condemnation of surface irrigation as "out-of-date" in dry areas, such as Agricultural Stability Zone 4 of Syria is certainly not justified. Surface irrigation deserves a more differentiated view. Farmers with lower quality water usually have no alternative for staple food production in such areas. Farmers like well owner No. 27 from Atshaneh village proved that surface irrigation, with good land levelling and diligent irrigation management can easily top the water use efficiency of sprinkler irrigation under near average seasonal rainfall conditions (WUE_i > 20 kg/ha·mm; EC_i 3.2 dS/m; P = 235mm).

Barley was apparently not worth irrigating unless it served to bridge a serious gap in moisture supply at a crucial development stage. However, this statement does not take into account the fact that the farmers are using barley – which is more in the case of irrigated production - as ration for sheep fattening, a largely profitable enterprise. Similarly, the irrigation of barley for the purpose of rearing sheep in early spring, when other grazing sources are rare, is a profitable activity. Especially lambs can grow well on the fresh barley shoots. Sprinkler irrigation is the method of choice, because it stimulates vegetative growth, at least if the water is not saline and the air temperature still moderate. The farmers are watering barley quite intensively until tillering. Then the sheep must be kept out, not to harm generative growth further than already the case from the reduction of assimilating biomass. Generally, barley is not receiving much water after grazing has stopped.

On average, irrigating cumin was profitable, however, profitability depends on the market price of cumin, which undergoes frequent fluctuations. In the context of this study, a price of near 50 SL/kg was assumed representative as cumin prices were fluctuating within a range of about 30 SL/kg to 70 SL/kg. Irrigating cumin after flowering and with an EC of more than 6 dS/m was usually not beneficial. In some cases too much water boosted the growth of weeds that ended up suffocating the tiny plants. Cumin cultivation is labour intensive. Weeding and harvesting were quite costly if cheap family labour was not available. Herbicides, such as Afalon® could be applied without harm to the host crop only during the early development stages.

Growing vegetables appeared to be quite financially attractive, besides being a source of healthy food that carries an opportunity benefit for not having to be purchased at higher rates than the production cost and transported from far. However, this enterprise requires experience, skills and a considerable amount of labour. Plots of 5 donum (0.5 ha) demand about 1200 labour hours or 200 man-days per summer season. Investment costs for drip equipment were approximately 100,000 SL/ha with short depreciation periods for tubes and fittings. Sufficient income is therefore needed to pay back the investment. Some risks remain in form of market price fluctuations and diseases or pests. Good quality water (< 4 dS/m) is conditional, since many vegetables, for example cucumber yield less than 50% of their potential at an EC of the irrigation water above 4 dS/m (Ayers and Westcot 1994). According to Tubeileh et al. (2004), care must be taken with intercropping of olives and vegetables, as they could be a source of *Verticillium* wilt for the trees.

In view of the relatively low irrigation requirement of olives trees, the economic efficiency of applying water to olives was found to be high. Whereas the assumption that olives do not yield without irrigation or water harvesting in Khanasser valley may not be true in exceptionally good rainfall years, the yield of rainfed olives in the valley remains below a commercially lucrative level under average rainfall conditions. The popularity of olive trees as a potential source of income was evidenced by the cumulative number of trees planted (Tubeileh et al. 2004). With sufficient quality water (~ 6 dS/m; Gucci and Tattini 1997), more land than water, family members who can help with the harvest, and with knowledge of tree husbandry, olive groves are clearly of interest to farmers in Khanasser valley. Provided Syria manages to further promote export sales of good quality olive oil, the price level should remain profitable.

With few options available, the Khanasser farmers usually opt for a mix of products, practicing risk minimization. Unknown external factors, such as marketing, prices and policies make rational optimization of water resource use a difficult task. On most farms land is not the limiting production factor. Besides water, being the scarcest, labour availability can also be decisive. Farmers with sheep have a preference for barley, those with access to family labour opt for summer crops or cumin if they speculate on a short-supplied market, and those with few children to help in agriculture might prefer extending the irrigated area grown with wheat. Of course, the construction of wells and the purchase of pumps and motors or pressurized irrigation systems require capital, which poorer farmers simply lack. Therefore the financial resources, including income from activities outside the farm, also determine what is feasible.

The crop rotation in this marginal environment is fairly monotonous. So far, only crops, which can provide some yield without irrigation, have occupied a lasting position in the production system. This only confirms that Khanasser farmers are avoid risks and do not prefer to depend entirely on irrigation. It would be most desirable to increase the diversity of the current crops rotation, for example, with drought resistant legumes and oil crops. Sturdy windbreaks, which produce fodder or wood, could reduce advective evaporation and save some soil moisture for better plant production. Manuring the Khanasser soils is expensive, but it is worth the investment. Apart from creating better soil fertility and structure, manure also improves soil moisture characteristics (Martens and Frankenberger 1992). Not only irrigation, but also the right management of soil moisture in rainfed systems can help improve the productive and economic potential in dry areas. As long as it remains within the sustainable limits (~ 150mm on around 600 ha), irrigation is acceptable in Khanasser valley, but one should keep in mind that the economic benefit from irrigation is often marginal and sometimes negative. Some farmers are helping themselves with record keeping and simple accounting to check profitability and keep past agronomic and economic data for reference.

Summary and Conclusions

Since the water level was predominantly stable during the period of observation and since the storage coefficient found during pumping tests was not high act indicated conditions of responsiveness to changes in storage. It was concluded that at the present rate, groundwater use in Khanasser valley was largely sustainable and in balance with an estimated 2-3% average annual net recharge. At 50-60 l/capita·day, domestic water use including the watering of sheep consumed roughly 25% of 1.3 million m^3 annual abstractions from the first aquifer. The rest was consumed by irrigation. From the water balance estimate, an average seasonal abstraction of 150 mm/ha from the first aquifer on 600 hectares was considered acceptable. This finding was largely credited to a change in the composition of the irrigated area starting at the end of the nineties, with more and more olives and the near total disappearance of cotton after it was banned from tube well irrigation in Agricultural Stability Zone 4.

Growing cumin had become quite common in the crop rotation, and some of it was irrigated. This made sense in case of a significant deficit before flowering, provided, the water was of an appropriate quality. Barley was unattractive as a source of cash income by itself. However, the sheep economy benefited from an increased production of ration feed and a source of grazing on sprinkler-irrigated fields after the birth of lambs in early spring. Wheat accounted for 50% of the irrigated area (about three-fourth of it under sprinkler irrigation) and 60% of irrigated volume. In view of a high irrigation productivity (6-8 kg/ha·mm), labour productivity and considering the price of wheat during the period, at the product price of the period of observation, wheat was still a good source of income for the farmers of Khanasser valley: 48 Syrian Lira per ha·mm and about 50 SL per family labour hour (~1 US $) with application of 140 mm (sprinkler) and 360 mm (basin) and corresponding yields of around 2400 kg/ha (sprinkler) and 3500 kg/ha (basin).

Family labour was an asset for those farmers who ventured into vegetables or olives due to the high labour requirement. On the observed farms, drip-irrigated vegetables were better supplied with water and therefore more productive. With good performance and sufficient demand of vegetable products, the income per ha could be as high as 84,000 SL/ha, but this required 2400 labour hours. Olives were also labour intensive, especially at harvest, which becomes costly without cheap family labour. The net benefit per unit of good quality water applied to well-adapted olive varieties with proper management was highest: around 300 SL/ ha·mm at 75 mm/ha for mature orchards. In a water-scarce area like Khanasser such high water productivity is an advantage. Due to related costs, an incremental benefit from irrigation cannot be taken for granted and water needs to be applied wisely to be profitable. The fragility of the natural environment was reflected by a fragility of the production system and its economic viability even with the use of irrigation. As socio-economic factors and environmental factors are intricately linked, the economic feasibility of agricultural enterprises is a key element conditioning the sustainable use of natural resources in marginal dry areas.

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Institutional Credit Support for Minor Irrigation: Focused on Groundwater Development

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Abstract

Minor irrigation particularly groundwater schemes are largely dependent upon mobilization of institutional credit and to a lesser extent on private investments. Institutional credit is duly supported by the subsidy provided by central and state governments to promote and popularize minor irrigation investments amongst farmers. Institutional credit is thus provided both for private and community owned dugwells, tubewells, agriculture pumpsets, energization, river lift irrigation schemes as well as for water management schemes, such as, drip and sprinkler irrigation systems, underground pipe lines, and, percolation tanks.

In this paper, technical, financial and credit constraints related to financing of minor irrigation projects has been identified. The paper then provides different solutions to overcome the problems, in view of the targets set for minor irrigation projects by the Planning Commission of India. Adoption of innovative approaches, such as, (a) water conservation and water augmentation through large scale micro irrigation practices, (b) construction of rain water harvesting and groundwater recharge structures benefiting irrigation farm fields, (c) watershed development measures in the dry land areas, (d) recycling of water for non-potable uses, would be required to enhance efficiency of water use. The paper also identifies the need for coordination between different stakeholders such as technical department, NABARD, state government agencies, banks and other research institutions for rational exploitation of irrigation water potential to enable the country to achieve the goal of reaching a food production level of 400 - 450 million tons by 2025.

Introduction

India's total available and usable water resources are estimated at 1122 billion cubic meter (BCM), of which 690 BCM are from surface water and 432 BCM from groundwater. Against the available usable resources, 629 BCM are currently utilized for various purposes. Irrigation sector share of 524 BCM, alone accounts for more than 80% of the usable water resources. Other sectors include: 30 BCM in domestic and drinking water use; 30 BCM in industrial use; 9 BCM in the energy sector, and the balance of 36 BCM is lost due to evaporation. India's average annual food grain production during the last three years has been around 200 million tons, whereas the current food requirements are put at 220 million tons. The difference is met through the buffer stock maintained by the government. The required annual food grain demand by 2025 for a projected population of 1.39 billion would go up to 400 to 450 million tons to meet not only the subsistence needs, but also to generate sufficient export surplus.

Irrigated Agriculture Perspective - 21st Century

In the coming few years in India, irrigation sector will not be able to utilize unlimited quantity of water. National Water Policy (Ministry of Water Resources, GoI) estimates for 2025 indicate that irrigation sector share would decline from the existing level of 83% to about 72%, mainly due to competing demands from other sectors such as drinking water and domestic sector. Estimates show that by 2025, irrigation sector share will require 611 BCM. The incremental production would require concerted efforts towards improving cropping intensity from existing 134% to 172%, besides enhancing the crop yield from the existing 2.2 tons per hectare (ha) to 3.5 tons/ha in irrigated area, and about 0.75 tons/ha to 1.50 tons/ha in un-irrigated (rainfed) areas. In other words, the existing ratio of gross irrigated area to gross cropped area at 40, which accounts for 56% the total food grain production in the country, has to go up to 50. This requires increasing the existing gross irrigated area from 81 million hectare (M ha) to 125 M ha by 2025. Achieving these targets would need large scale adoption of water management and water conservation practices to help improve the water use efficiency, conjunctive use of surface water and ground water, artificial recharge of ground water, and, rain water harvesting through large scale adoption of farm pond, check dam, and percolation tank structures. Simultaneous treatment of the watersheds to arrest run-off water in water scarce and water deficient areas is a priority for many parts of the country. Thus, *irriculture* (irrigated agriculture) in the 21st century has to proceed differently on a resource (water and land) management concept, so that it sets the path for a second Green Revolution of food sufficiency and high marketable surpluses.

Significance of Minor Irrigation Potential in Irrigated Agriculture

The ultimate irrigation potential (UIP) comprising of major, medium, and minor irrigation sub-sectors is estimated at 139.95 M ha, of which minor irrigation potential at 81.45 M ha (17.4 M ha surface water and 64.05 M ha ground water) accounts for 58.2% of the total available irrigation potential. So far about 69% of the UIP has been harnessed. The share of groundwater accounts for more than 50% of the total irrigation potential developed so far in the country. By the end of Ninth Five Year Plan (FYP) (1997-2002), it is estimated that minor irrigation potential of 63.47 M ha (13.45 M ha surface water and 50.02 M ha groundwater) has been cumulatively created. Thus, minor irrigation, in general and groundwater in particular, has been playing a very important role in creation of overall irrigation potential leading to enhanced agricultural production in the country. The Tenth Five Year Plan (FYP, 2002-07) emphasizes on minor irrigation due to its advantages and need for early harnessing of resources to meet higher demand for food production. The Tenth FYP target for creation of additional minor irrigation potential is 16.66 M ha, which is twice the value of the achieved target of 7.24 M ha of Ninth FYP.

Role of Institutional Credit in Minor Irrigation Development

Minor irrigation particularly groundwater schemes are largely dependent upon mobilization of institutional credit and to a lesser extent on private investments. Institutional credit is duly supported by the subsidy provided by central and state governments to promote and popularize minor irrigation investments amongst farmers. The basic principal of subsidy provision is based on growth and equity, both from resource development and credit dispensation point of view.

Credit is provided by Rural Financial Institutions (RFIs) i.e., banks with re-finance support from the National Bank for Agriculture and Rural Development (NABARD) wherever necessary. As an apex institution, NABARD guides banks in agriculture and rural development activities of the country, besides ensuring credit delivery in the rural areas. Institutional credit is thus provided both for private and community owned dugwells, tubewells, agriculture pumpsets, energisation, river lift irrigation schemes as well as for water management schemes, such as, drip and sprinkler irrigation systems, underground pipe lines, and, percolation tanks. Medium and long-term (MT/LT) loans for minor irrigation structures are provided to individual farmers, groups or cooperative societies by the State Cooperative Agriculture and Rural Development Banks (SCARDBs), the State Cooperative Banks (SCBs), the Regional Rural Banks (RRBs) and the Commercial Banks (CBs), who in turn avail re-finance from NABARD.

Institutional credit for minor irrigation during the First FYP (1951-56) was negligible, but thereafter, it has steadily grown from Rs.1.92 billion during the Second FYP (1956-61) to Rs.119.75 billion during the Ninth FYP (1997-2002). The demand for credit under minor irrigation sub-sector has shown an upward growth and a similar growth in future is also expected.

Direct Financing to State Irrigation Projects under Rural Infrastructure Development Fund

The Government of India (GoI) created Rural Infrastructure Development Fund (RIDF) to finance infrastructure development in the rural areas. RIDF is managed by NABARD, and it provides loans to the state government for completing existing infrastructure projects and new projects. In the irrigation section, RIDF finances completion of on-going state irrigation projects, particularly the minor and medium irrigation projects, which remained incomplete for want of funds. NABARD provides loans out of this fund to state governments so that capital locked in such projects for years could be made productive.

Under RIDF I to IX (1995-96 to 2003-04), so far, 229 major, 205 medium and 90,925 minor irrigation projects have been sanctioned to twenty-five states. The aggregate loans for these projects amount to Rs. 122.89 billion. In economic terms, these investments are expected to create an additional irrigation potential of 8.55 M ha, generating gross domestic production of Rs. 97.12 billion,besides creating 4.46 million jobs and 1209.5 million man days of non-recurring employment. Out of the sanctioned projects, 76 major, 113 medium and 45,060 minor irrigation projects have so far been completed creating estimated additional irrigation potential of 5.40 M ha.

Watershed Development

In India, rainfed agriculture contributes 44% of the annual food grain production i.e., about 88 million tons are grown over 105 M ha of arable land, which in turn constitutes about 70% of the net cultivable area. Even after realizing full irrigation potential, 50 per cent of arable land will still remain under rainfed conditions. The significance of the rainfed agriculture can be gauged from the fact that it supports 90% of the oilseed production and 70% of coarse cereals, besides supporting nearly 66% of cattle wealth and 40% of Indian population.

Watershed development in such areas is a significant intervention in terms of run-off arrest, moisture retention, and groundwater recharge. Soil conservation and land use management in the watershed areas ensure sustainability of agriculture and livelihoods of the people. NABARD with assistance from KfW, a German development financing agency, implemented participatory watershed development in more than 0.1 million hectare (ha) in twenty-one districts of Maharashtra state. The watershed management programme has been successful largely due to peoples' participation. The various tangible and intangible benefits derived through such participative watershed interventions are given in Box 1.

Box 1. Tangible and intangible benefits – lessons from participatory watershed management program in Maharashtra, India.

- Improved financial rates of return ranging between 25% and 35%;
- Drinking water scarcity in the villages has been effectively tackled;
- Villages which once experienced off-season migration are now reporting nil or minimal migration;
- Visible secondary impact in terms of improved quality of life and habitats, besides increase in school attendance;
- Induced groundwater recharge resulting in water table build-up and increase in the population of irrigation wells;
- Improved agricultural production in term of post development incremental increase in the crop yield and crop diversification in *Kharif* and *Rabi* seasons;
- Improvement in the economic conditions of the landless laborers due to in-situ, round the year availability of work and wages during and after the construction of projects;
- Improvement in the availability of green fodder supporting expanded dairy activities;
- General improvement in the demand for credit (on an average credit uptake equivalent of 40% of the amount invested in soil and water conservation measures is observed);
- Strong community involvement, besides improvement in loan repayment.

Emerging Issues in Minor Irrigation Sector

NABARD has been periodically conducting various studies related to investment, monitoring and evaluation, to identify opportunities and constraints in providing credit for rural infrastructure projects. NABARD studies on minor irrigation projects have identified various constraints and reasons for lower achievements of performance targets. Broadly, there are two main constraints of project financing: technical and financial and credit.

Technical constraints

Technical constraints in the minor irrigation projects are different for the surface and groundwater irrigation projects. Surface water projects can be divided into two categories: (a) reservoir and tank irrigation projects, and, (b) cooperative irrigation projects. In the case of reservoir and tank irrigation projects, there are technical constraints pertaining to silting, technical design and management, and lack of funds for maintaining reservoirs and tanks. Technical constraints in the cooperative lift irrigation projects are those related to faulty technical designs, flouting of technical specifications and guidelines, and non-availability of reliable electricity supply resulting in either over-irrigation or under-irrigation of crops (Box 2).

Technical constraints in case of the groundwater irrigation projects relate to well failure and failure of borewell programs to reach eastern Indian states, conversion of safe blocks/watersheds into dark and over-exploited, non-enforcement by state groundwater department of guidelines pertaining to spacing and groundwater assessment studies (Box 2).

Box 2. Technical constraints for surface irrigation projects

Reservoirs and tanks

- The supply channels of old tanks have been silted due to lack of proper operation and maintenance (O&M) care; desilting work is an ineligible activity under institutional finance;
- The foreshore lands of tanks have been encroached upon by farmers for cultivation making construction/repairs difficult;
- Distribution channels beyond sluice opening could not be completed in a number of tanks due to fund constraints, land acquisition, and project affected people (PAP) issues, besides delay in obtaining Forest, Public Works Department, and Railways clearances;
- Non-execution of on-farm development works (up to 1.5 cusec outlets) more particularly in large minor irrigation tanks;
- Concurrent design changes leading to cost and time overruns;
- Effective submergence exceeding the limit with respect to Irrigable Command Area (ICA); and
- Inadequate annual provisions, in general, for O&M public grants leading to deterioration of both head works and distribution networks.

Cooperative lift irrigation

- Over designing of head works and distribution network to suit unauthorized/non permissible use of higher percentage of ICA for perennial crops like sugarcane than what is allowed by the Water Lifting Permissions (WLPs), mostly in case of Sugar Factory (SF) sponsored projects;
- Flouting of WLPs issued by Irrigation Department (ID) for *Kharif* and *Rabi* seasons to grow perennial crops, mostly sugarcane;
- Non observance of sanctioned technical norms/parameters; often project execution is half way through before applying for loan/refinance by Lift Irrigation (LI) Societies through primary banks/branches;

- Inadequate availability of water at the source point in river beds etc., due to unauthorized tapping by similar structures in the upstream;
- Non availability of adequate and continuous electric supply voltage leading to under and/or over irrigation with associated problems including reduced crop yields or crop failures; and
- Other associated problems, e.g., leakages, pipe damages etc., affecting irrigation schedule under Cooperative Lift Irrigation Scheme (LIS) leading to post commissioning sickness/failure of LIS.

Groundwater projects

- Though program of 'Free Boring' was much accelerated in Uttar Pradesh state; it could not be promoted to a desired level in other states like Bihar, Assam and West Bengal;
- Large scale well failure of both open wells and bore wells in hard rock areas due to absence/ inadequate services from State Ground Water Departments (SGDs) for siting of well source, besides non availability of ground water worthy maps on user friendly scales (1:5000 or 1:10,000) especially for use by program implementing banks/branches;
- Large number of blocks/*mandals*/watersheds coming under critical (dark) and overexploited (red) categories with depleted water levels where free flow of institutional credit is not available;
- Targets for construction of open wells and bore wells in hard rock areas fell short by nearly 40 per cent due to drought conditions and declining water levels;
- Selection and installation of higher horse power (HP) electric and diesel pump sets than what is required as per prevailing hydro geological conditions of the area and that too not conforming to IS:10804 of 1994 for Complete Pumping System (CPS) leading to overdraft conditions/ground water mining, besides higher consumption of both electric power and diesel oil;
- Non observance of spacing criteria under privately constructed wells due to absence of State Ground Water Legislation;
- State Ground Water Departments (SGDs) not carrying out ground water assessment as per Ground Water Estimation Committee-1997 (GEC-1997) revised methodology/norms leading to non-redressal of farmers' grievances belonging to 'Critical' and 'Overexploited' blocks/*mandals*/ watersheds declared with respect to earlier GEC-1984 methodology/norms. Similarly, there is a general apathy on the part of SGDs to conduct ground water assessment based on micro watershed analyses/studies to permit new well program in feasible pockets within such dark and critical blocks/*mandals*/watersheds; and
- Slow pace of energization in 10 eastern and north eastern states resulting in widening of gaps between potential created and utilized, besides undependable and erratic power supply causing shortfalls in achievement of productivity targets.

Financial and Credit Constraints

Financial and credit are the second set of constraints. The main issues pertain to lack of resource availability with the central and the state government, poor performance of irrigation schemes, unsatisfactory recovery of credit, and poor land records including fragmented land holdings, which restricts access to credit. Financial and credit constraints as identified by NABARD studies are listed in Box 3.

Box 3. Financial constraints

- Inadequate central and state resource availability for new works. Most of these works are undertaken by state, *Panchayati Raj Institutions* (PRIs, village elected bodies), and, Rural Development Department, where priorities clashed year after year including non-observance of fiscal discipline particularly in Centrally Sponsored Schemes (CSS) implemented by the state governments;
- Poor performance of lift irrigation schemes due to non repayment of bank loans and poor O&M during post construction stage by groups and cooperatives;
- Delay in loan appraisal due to cumbersome procedure and documentation insisted by banks;
- Unsatisfactory recovery position of banks leading to reduced lending eligibility. Besides, in some major states, SCARDBs have become weak due to mounting Non Performing Assets (NPAs) necessitating rehabilitation and adoption of reform packages;
- Delay in sanction and release of subsidy;
- High cost of micro irrigation systems;
- Diversification to other activities like farm mechanization, non-farm sector and other priority sectors and contribution to Rural Infrastructure Development Fund instead of direct lending to individuals or group of farmers;
- Sizable number of small and marginal farmers were not having access to credit because of fragmented land holdings; and
- Inadequate land records.

Strategies for Boosting Minor Irrigation Institutional Investments

The Planning Commission has laid a major emphasis on accelerating the pace of minor irrigation development, especially groundwater schemes through institutional investments during the Tenth FYP (2002-07). Accordingly, it is proposed to harness 14.66 M ha of minor irrigation potential (13.93 M ha ground water and 0.73 M ha surface water) involving credit assistance of Rs. 3091.5 billion for new programs. The programs would include: approximately 1.6 million dugwells, 2.6 million shallow tube wells and bore wells, 7288 deep tubewells, 53 lakh agriculture pump sets, 7 lakh ha cooperative lift irrigation schemes, 0.86 million ha sprinkler irrigation units and 0.7 million drip irrigation units. Besides the new programme, there is a provision of Rs. 107.3 billion for replacement of old structures. In addition to these programs, the plan outlay has earmarked Rs. 442.7 billion for energization program for agriculture pumpsets. The total financial assistance envisaged during the Tenth Plan is of the order of Rs. 3641.5billion. NABARD with the active participation of various RFIs and other related agencies is to play a crucial role in steering various policies and programs with suitable modifications so as to ensure purveying ground level credit disbursement at an accelerated pace to meet the country's food demand targeted at 350 million tons by the end of this decade. The various initiatives related to credit planning and financial are given below.

Credit Planning Initiatives

In order to harness the groundwater potential of the order of 13.93 M ha, it is proposed to annually create 2.786 M ha of additional irrigation potential throughout the Tenth FYP period through formulation of banking plans and area development projects for dugwells, shallow tubewells and bore wells, medium deep tubewells, agriculture pumpsets (diesel and electric), and, underground pipe lines. These will be covered under individual and group financing in ground water resource rich states and districts. Towards achieving this objective, adequate credit flow for minor irrigation sector has to be ensured.

Maintaining groundwater quality is critical for sustaining economic development and growth. In order to maintain ground water quality to sustain the projected usage, a well-planned water resources management strategy for the country is needed. The prevailing hydro-chemical regime has to be well established by a better network and optimum frequency of water sampling points for baseline information, trend analysis and surveillance. Quality zonation maps including groundwater pollution levels of specific areas, the likely areas of pollution beyond recoverable stage and the zones where the same can be controlled would have to be demarcated. The priority of water use viz. drinking water, irrigation, industrial and cattle requirement - and extent of feasible extraction for each zone are to be demarcated for further studies including chemical and microbial contamination of groundwater.

Government of India has formulated a credit linked subsidy program entitled *"On Farm Water Management Scheme for Increasing Crop Production in Eastern and Northeastern States of India"*. The objective of the scheme is to harness vast groundwater potential available in ten eastern and northeastern states, for implementation during 2001-02 and Tenth FYP period. Under the scheme, subsidy is provided to eligible farmers for shallow tubewells, dugwells, low lift points and purchase of agriculture pumpsets in ten states: Assam, Arunachal Pradesh, Manipur, Mizoram, Bihar, Jharkhand, Orissa, Chattisgarh, Uttar Pradesh and West Bengal. An amount of Rs. 11.5 billion has been earmarked towards 30% subsidy for the years 2001-02 and 2002-03. NABARD is the nodal agency for preparation of banking plans and release of subsidy as also monitoring the implementation of the scheme. In all 70,000 structures have been installed upto October 2004. Similarly, Million Shallow Tubewell Programme with 30 percent capital subsidy assistance has also grounded 175,000 shallow tube wells in Bihar upto October 2004. During the last year NABARD had worked with government and bankers in Bihar and could influence banks to finance more than 50,000 minor irrigation structures under this scheme.

RIDF intervention has created an additional surface water irrigation potential of 5 M ha between 1995-96 and 2003-04. The impact of this intervention has been in terms of rejuvenation of groundwater in the downstream of the newly created reservoir projects, activation of well fields in their canal command areas, besides availability of about 6 per cent committed share of their reservoir waters (amounting to creation of 0.26 M ha irrigation potential) for development through lift irrigation schemes. The exploitation of ground water in such areas has to be planned through formulation of reservoir or command specific banking plans under institutional lending program. All these credit interventions would be possible only when the respective state governments annually allocate funds for operation and maintenance of these newly created irrigation structures.

Another initiative is to enhance credit support to *micro irrigation systems* with simultaneous reduction in the quantum of subsidy in a phased manner, besides effecting reduction in their unit costs by doing away with the sales tax and excise duty and simultaneously initiating other suitable measures. The Task Force on Micro Irrigation (January 2004) has recommended to add about 2.0 M ha and 1.0 M ha under drip and sprinkler irrigation systems during 2004-07, respectively. This would require formulation and vigorous implementation of state wise and district wise banking plans with emphasis on large scale adoption by states like Himachal Pradesh, Jammu and Kashmir and northeastern states where the coverages under horticulture crops have grown over the years but are lagging in adoption of micro irrigation systems. Similarly, states like Punjab, Haryana and Uttar Pradesh who are agriculturally advanced but slow in adoption of micro irrigation system; and states facing frequent droughts e.g., Madhya Pradesh, Gujarat, Rajasthan and Orissa should be the focused areas for promotion and popularization of micro irrigation. In states where adoption of micro irrigation is in advanced stage e.g., Maharashtra, Tamil Nadu, Karnataka, Andhra Pradesh and Kerala where on an average 60,000 ha are annually brought under micro irrigation, efforts will have to be intensified to enhance the coverage in various fruit and cash crops with strong support from the state government.

Yet another initiative is to encourage small lift irrigation schemes (up to 40 ha) for individuals or groups, medium lift irrigation schemes (up to 250 ha) in cooperative sector and big lift irrigation schemes (up to 500 ha) on a very selective basis to sugar factory-sponsored schemes in cooperative sector. Program also encourages low lift point schemes (LLP) involving minimal engineering (3-5 HP electric, diesel and petrol-start-kerosene driven pumpsets with 200 - 300 m length/ 4 kg per sq cm pressure class rigid PVC pipes) through formulation of area development plans exclusively for tribal and hilly areas based on identified surface stream potential generally available upto February/March.

Promoting rainwater harvesting (RWH) through large scale financing of farm pond, weir, check dam schemes, especially in hard rock areas (central and southern peninsular India) where groundwater is in a state of depleted conditions is another initiative. Similar efforts also may have to be made in drought prone areas especially in the plateau areas of Rajasthan, Madhya Pradesh, Gujarat and Orissa. A centrally sponsored water-harvesting scheme for SC/ST farmers has been operationalised by NABARD (since August 2004) with a credit linked capital subsidy of 50% to the extent of Rs.100 crore. The plan also encourages drainage development schemes (DDS) coupled with conjunctive use of surface water and ground water especially in canal commands to avoid water logging in areas beset with:

- Shallow water table conditions (e.g., Punjab, Uttar Pradesh and parts of Rajasthan and Maharashtra);
- Surface run off stagnation (e.g., Andhra Pradesh, Haryana, Gujarat, Kerala, Orissa, Punjab, Tamil Nadu, Uttar Pradesh and West Bengal); and
- Saline/alkaline lands (e.g., Punjab, Haryana and parts of UttarPradesh).

This would require enhanced public sector funding towards the development and maintenance of main and intermediate drainage (M&ID) systems besides, all other on farm development (OFD) works under the Command Area Development

Program (CADP) run by central/state governments. In addition, better integration of the engineering, agriculture and extension functions in managing the system is needed.

The government has also drawn plans to encourage schemes for construction of new tanks, renovation and modernisation of existing tanks to restore lost potentials, especially in the tribal and hilly districts of states like Madhya Pradesh, Maharashtra, Andhra Pradesh, Tamil Nadu, Orissa and Karnataka with people's participation and NGOs. It will also involve ground water recharge (GWR) schemes with the help of State Ground Water Departments or State Minor Irrigation Departments in areas where water levels are persistently declining for sustainance of wells facing partial or complete failures e.g., Maharashtra, Rajasthan, Saurashtra in Gujarat, Tamil Nadu, Karnataka and Andhra Pradesh. The plans also encourage large-scale reuse of treated water for irrigation under guidance from Central and State Pollution Control Boards. Besides, steps should be taken to protect ground water resources from pollution.

Financial Initiatives

Financial initiatives as identified in the plan are as follows:

- Continue existing refinance quantum of 90-100 per cent of the bank loan depending upon the category of borrower, agency and region;
- In view of the significance of minor irrigation as an important input for accelerated growth in agriculture and the National Agriculture Policy to double the food grains production by the end of this decade, NABARD has considerably reduced the rate of interest on refinance for lending under the sector by various agencies. The present rates of interest are 5.50 per cent for loan size up to Rs. 50,000. For loans above Rs. 50,000, refinance will be at the interest rate of 5.50 per cent for the northeastern region (including Sikkim and Andaman & Nicobar Islands) and 6.25 per cent for all other regions. This concession is also available for minor irrigation disbursements made under other development schemes.
- Existing norms of drawal of re-finance for wells, pump sets, small lift irrigation schemes under Automatic Re-finance Farm Sector- Minor Irrigation (ARFS-MI) to continue in white or safe areas, whereas for larger investment outlays, formulation of area development projects and banking plans for prior sanction by NABARD may have to be accelerated in resource rich ground water worthy areas both in hard rock and alluvial formations;
- In the case of drip and sprinkler schemes, where higher amount of subsidies are involved, banks are advised to extend credit for total loan amount including subsidy after assessing the overall viability of the schemes and NABARD would extend refinance on the basis of bank loans;
- Promoting innovative schemes with the help of state governments such as, creation of "Private Ground Water Markets" in water logged and salt affected command areas. The schemes would finance projects in hard rock areas beset with excessive use of ground water for growing cash crops such as sugarcane, and banana, for the benefit of adjoining non command areas; and

- Promoting commercial agriculture and contract farming in identified groundwater sanctuaries on pilot basis.

Emerging Issues

Some critical issues that are affecting the pace of irrigation development need focussed attention:

Energization of Agriculture Pump Sets

Sluggish energization of agriculture pump sets is resulting in widening of gap between potential created and potential utilized. There are 1.3 million financed wells awaiting energisation (in terms of paid pending applications) for the last two to five years by the State Electricity Boards (SEBs). During the Tenth FYP (2002-07) another 3.7 million electric pump sets would be required to be energised under institutional investment program. The SEBs therefore would be required to augment their resources for system improvement of distribution network and also enhancing the demand based distribution network. A related issue is the pricing of power supplied to agriculture sector. Cost recovery would be an imperative that could lead to accelerated energisation of agriculture pump sets.

Micro Irrigation

High cost of micro irrigation system i.e., drip and sprinkler units (average per ha unit cost varying between Rs. 30,000/- for widely spaced crops and Rs. 60,000/- for closely spaced crops) are one of the major constraints in accelerating the pace of institutional investment. The Indian National Committee on Irrigation and Drainage (INCID) constituted for Drip Irrigation System under Ministry of Water Resources in 1994 and National Committee on Use of Plastics in Agriculture and Horticulture (NCPAH) constituted for Sprinkler Irrigation System under Ministry of Agriculture in 2001, have highlighted the issue of high cost of micro irrigation as the major constraints in large scale adoption. These issues are even prevalent in states, which are agriculturally advanced and have brought large areas under horticulture crops (e.g., Punjab, Haryana, Himachal Pradesh). The committees have suggested bringing down the cost through waiver of all types of taxes (sales tax and excise duties) both on raw materials and finished products of micro irrigation systems. The Task Force on Micro Irrigation has also made similar suggestions on reduction of taxes and duties in 2004.

Groundwater Reassessment

Groundwater reassessment based on Groundwater Estimation Committee-1997 methodology and norms have not been completed by many State Ground Water Departments (SGDs) affecting the financing of groundwater programs as large number of blocks/ *mandals*/ watersheds are turning into overexploited, critical and dark categories. The issue is that of safe and sustainable exploitation and use of ground water needs to be put in place. It is expected that revised groundwater assessment will be completed by March 2005.

People's Participation in Community Irrigation Projects

RIDF financing has created 5.40 M ha of estimated irrigation potential through combination of projects till 2004. Effective turn over of these projects through Participatory Irrigation Management (PIM) or Water Users' Associations (WUAs) is one of the conditions of sanction of projects to the state governments. In fact, most of the State Irrigation Departments (SIDs) and State Minor Irrigation Departments (SMIDs) are slow on effectively turning over the projects to people. Participation is critical for maintaining the efficiency of structures and their optimal use in an equitable manner.

Creation of Private Groundwater Markets

Creation of private groundwater markets on pilot basis, especially in the water logged areas affected by water intensive crops (e.g., Maharashtra, Karnataka, Gujarat, and Madhya Pradesh) could be developed as 'Ground Water Sanctuaries' through willing entrepreneurs in private sector for sale of water to farmers belonging to adjoining non-command areas. This would require state governments to take suitable legislative measures to throw open such groundwater sanctuaries, which are mutually beneficial to command and non-command farmers for private sector participation.

Looking Ahead

Minor irrigation potential has a significant place in the country's irrigated agriculture. Its development is largely dependent upon institutional credit requirements. Nearly 80% of the institutional credit disbursed under minor irrigation is on account of development of groundwater potential. In order to boost credit disbursement more attention will have to be paid on systematic development of groundwater resources because of its inherent advantages.

From the preceding overview and analysis of the programs, it is apparent that the irrigation programs involve substantial amount of coordinated efforts from different stakeholders, not only in creation of irrigation works (wells and reservoirs), but also in undertaking periodic investigations and planning of both groundwater regimen (hard rock and alluvial areas) and the river basins of the country.

Adoption of innovative approaches, such as, (a) water conservation and water augmentation through large scale micro irrigation practices, (b) construction of rain water harvesting and groundwater recharge structures benefiting irrigation farm fields, (c) simultaneous watershed development measures in the dry land areas, (d) recycling of water for non-potable uses, would be required to enhance efficiency of water use. Diversification of agriculture to grow more cash and commercial crops on one hand, and increasing production and productivity levels through efficient use of inputs including water on the other, would be vital for food security in future.

In short, one cannot overemphasize the fact that water is a perennial but scarce resource. Efficiency and productivity of water use has to be the prime consideration in agriculture. While mechanisms for conservation and optimal use are available and could be put in place, each time an irrigation resource is tapped, the question of what is the best possible use of this water needs to be answered. The sub-optimal use of water in some states has led to environmental degradation and adverse impact apart from reducing productivity of agriculture. An approach to optimal use of water calls for both crop and land use planning.

A related issue pertains to pricing of irrigation water where the irrigation structures and delivery mechanisms are owned by the states. Uneconomic pricing has resulted in unwarranted and exaggerated use of water leading to adverse impact. Appropriate pricing aimed at cost recovery would ensure that water is used for enhancing productivity and discourage unwarranted use. This would also ensure that resources are generated for maintenance and repairs of the existing structures. The Vaidhyanathan Committee's recommendations in this regard have not been implemented seriously by the states. It is high time that in the interest of the sustainability of agriculture the committee's recommendations are taken up in right earnest. An additional issue is that of rainfed lands which constitute the majority of the cultivable land in the country. Dr. Swaminathan had suggested that there should be a goal of bringing at least one million ha each year under watershed development program. While the task seems immense, a mission approach could deliver the results required which are critical for the future of large number of resource poor farmers engaged in agriculture in such regions. Finally, we are all aware that water is not a mere input in agriculture; it is a source of livelihood that requires systematic planning and careful use.

It is important to recognize that in water sector, there is no single solution uniformly applicable to all the agro-climatic regions and sub-regions of the country. Each approach of treatment and development is valid in its own right and has to be given equal priority along with other strategies and solutions. Coordination and effective participation by various stakeholders for resource care and sustainable development whether institutionally, privately or through public is very essential. It is in this backdrop that NABARD, the state water resources departments (both ground water and surface water), banks and other concerned departments and research institutions must join hands to coordinate their efforts in boosting rational exploitation of irrigation water potential to enable the country to achieve the goal of reaching a food production level of 400 - 450 million tons by 2025.

Understanding and Managing the Water–Energy Nexus: Moving Beyond the Energy Debate

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Abstract

Energy and water are key instruments for agricultural production and their interlinkages pose significant management challenges. Lack of appropriate energy policy and policy to deal with management of groundwater has not only contributed to over-exploitation of groundwater; it has also resulted into a nexus. Perverse incentives provided as part of the energy policies have led to economic inefficiency in the performance of the electricity utilities, playing havoc with the energy economy of the country and viability of the energy sector. Analyzing the growth in use of groundwater and energy for pumping coincides with India's overall development policy of attaining food security. However, much of the debate on water- energy nexus as an indirect approach for groundwater management has focused on the energy side of the nexus, ignoring the role of agriculture policy, especially those dealing with gaps in market linkages for agricultural products and role of minimum support price, which have greater influence on farmer's choice of cropping pattern and hence excessive groundwater use. Policies governing agriculture and energy are apparently dictated more by political populism rather than sound management strategies for sustainable resources development. Combined effect of these policies has resulted in the hydrological unsustainable over-exploitation of groundwater. In this paper, the authors argue that there is need to further the debate on water-energy nexus beyond the realms of those focused primarily on energy policies.

Introduction

Despite a decade and half of economic reforms in India, agriculture remains the backbone of the economy and a direct and indirect source of livelihood for India's vast rural population. The recent estimates show that the agriculture sector accounts for 22% of the Gross Domestic Product (GDP), and provides livelihoods to 58% of the population (584 million people, GoI, 2004). In fact, energy (electricity) and water (irrigation) have emerged as key determinants of economic growth and social development in the rural areas in India.

Groundwater has become the mainstay of irrigated agriculture in India. Energy, especially electricity, has contributed significantly to the development and exploitation of groundwater resources, improving productivity and providing livelihood and food security (Shah et al., 2003). While energy and water have strengthened economic opportunities in rural areas and ensured food security, these are also threatening this very livelihood option. Groundwater resources in India are largely unmanaged, resulting in high possibility for its over-exploitation, thus threatening people's livelihoods and endangered drinking water supplies. This is further aided by energy policies and perverse incentives created by energy subsidies, inefficient electricity distribution system involving unreliable, poor quality and restricted hours of supply. Lack of appropriate energy policy has not only indirectly contributed to overexploitation of groundwater, creating a water-energy nexus, the energy policies have also, resulted in economic inefficiency of electricity utilities (State Electricity Boards), playing havoc with the energy economy of the country and seriously affecting the viability and reform process of the energy sector.

Much of the debate on managing the water – energy nexus has focused on intervening on the energy side of the nexus as an indirect tool for arresting the depletion of groundwater, which is addressing only half of the problem (Shah et. al., 2003; Sharma et. al., 2005). The indirect approach in energy policy has a technocratic bias, rather than the appreciation of the other side of the problem, the associated policy issues and political nature of the problem. Energy policy intervention, especially those policy measures initiated since electricity sector reforms have focused on either economic – raising electricity tariff for agriculture users – and/or technical – installing meters and doing demand side management to improve the pump set efficiency. The standard electricity reforms prescriptions have witnessed little buy-in from the farmers, as well as politicians. While individual farmers have opposed metering; collective action, and lobbying by farmer's groups have been effective in blocking tariff increase and payment of arrears. These collective actions of farmers have also found support from the political groups, who have used the means of waiver of dues and subsidized to free power as an instrument for rural development and to win farmer's vote.

Energy and water are key instruments for agricultural production. Irrespective of the changes in the energy policy, the demand for groundwater depends upon what farmers grow, which in turn is influenced by the support price policy, agriculture (food security) policy, and, market linkages. Government policies in the agriculture sector are multi-faceted and inadvertently encourage the production of water intensive crops over more water efficient commodities. Indian agriculture suffers from a mismatch between food crops and cash crops. Domestic production of pulses and oilseeds are still much below the domestic requirements. A distinct bias in agriculture price support policies in favor of rice and wheat has distorted cropping pattern and utilization of different inputs. Besides this, market for farm produces continues to be dominated by heavy procurement interventions by the government agencies.

Analyzing the growth in use of groundwater and energy for pumping coincides with India's overall development policy of attaining food security through Green Revolution technologies. The nexus that is visible today is due to the fact these policies did not change with time. That brings to another external factor – political - affecting the nexus: the rise of farmer's movement coupled with political populism in the late seventies and early eighties. The farmer's movement in southern states of Andhra Pradesh and Tamil Nadu brought the political intervention of free power. Almost parallel movement of farm lobby in northern and western India brought more subsidies in the agriculture sector in form of inputs and minimum support price for food crop procurement. Combined impact of these policies has affected the water and energy sectors. Breaking the nexus would require not just policy changes at the level of farm input subsidies, but also a realistic and strategic shift from minimum support price policy, and developing alternate product markets essential for crop diversification.

Water – Energy Nexus: Moving Beyond the Energy Debate

Water – energy nexus in India is a result of policy issues such as those dealing with groundwater, agriculture, and energy. Rapid development of high intensity of pump sets of smaller capacities scattered throughout the landscape makes water – energy nexus peculiar. Yet, another feature of the nexus is the existence of groundwater markets, where especially the small and marginal farmers depend upon the pump owners to buy water. Groundwater resources are largely unmanaged and the policies needed to deal with the problem are not yet in place. Agricultural policies, especially the procurement policies are such that they have encouraged farmers to continue growing more water intensive crops (rice, sugarcane etc.). Energy policies and economic incentives (or disincentives) for use of electricity for groundwater extraction, has resulted in almost zero incremental cost for the farmers. At the same time, inefficient electricity distribution system involving restricted hours of supply, with unreliable and poor quality has resulted in long hours of pumping by the electric pump owners.

The existing discussion on water energy nexus, attempts to capture a simple linear causal relationship between water and energy sector, as shown by the bottom part of the triangle in Figure 1. The causal effect for the energy-water nexus is not just due to inadequate energy policy or groundwater policy or the absence of any linkage between the two sector issues. Uncertainty of monsoon and existence of groundwater markets add further stress to the groundwater resources. This is a vicious cycle from the groundwater sector perspective. Energy sector policies provide electricity at a very low cost for agriculture and contribute to the socio-economic development of the rural areas. Due to shortages in electricity generation, and almost negligible return from supplying electricity to farmers (low/ nil tariff, non-payment), the utilities restrict the supply hours and provide it during off-peak hours. Lack of investments in strengthening the supply infrastructure by the utilities often results in frequent breakdowns and burnouts. Dispersed nature of electricity connections, means very little monitoring, and allows pilferages. This results in a vicious cycle, which the farmers mitigate by pumping for all the hours supply of electricity is available and in the process affecting the groundwater resources. These two vicious cycles are considered as the cause of the nexus. The nexus is complicated further by policies related to those of the agriculture and trade and procurement support policies, which influence the choice of crops grown.

Broadly, there are two approaches to arrest depletion of groundwater – direct and indirect. The direct approach for groundwater management has largely failed, as access to groundwater is through right of capture and the number of users is simply too large for effecting any regulations. In fact, despite being a common resource, inability to manage groundwater is a classical failure of common property resource management. In the absence of any effective legislation for groundwater management, indirect approach through energy policy intervention has been considered as an alternate option.

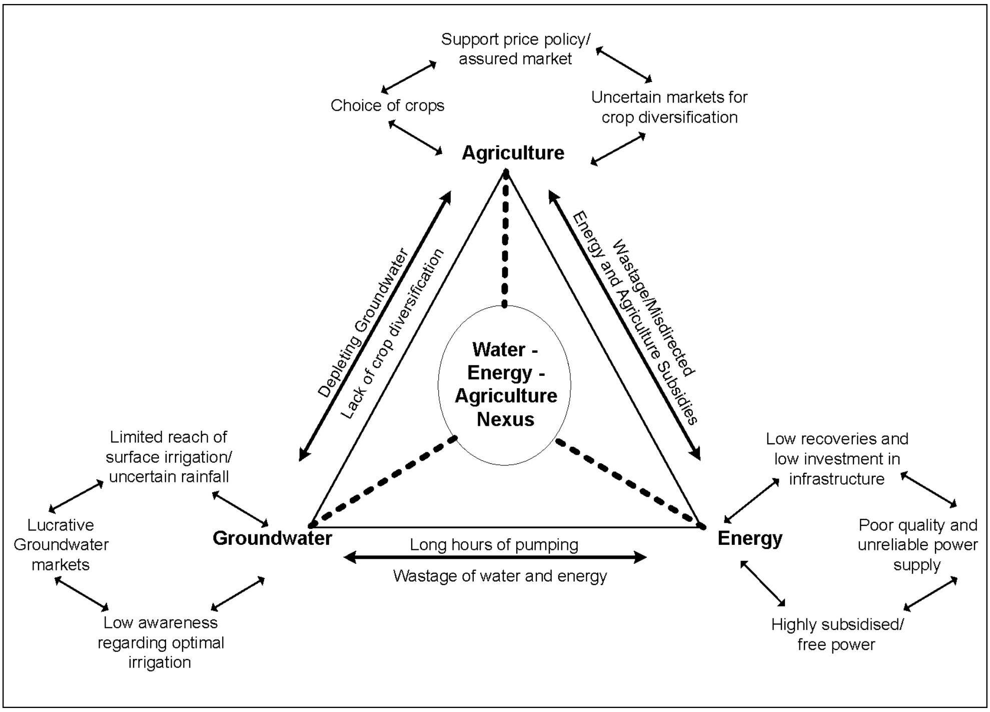

Figure 1. Water - energy nexus – moving beyond the energy debate

Energy policy as an indirect tool for groundwater management has twin advantages: one, it can be effective in arresting groundwater overexploitation, and, two, it will also lead to economic viability of the energy sector. The energy sector policies have focused either on technical solution of metering and demand side management, or through economic instruments of electricity tariff revisions. The policy prescriptions have emerged since the on-set of energy sector reforms, which views electricity supply to agriculture and poor recoveries as key factor for poor performance of electricity utilities in India. However, energy policy interventions have limitations, and given the standard prescription, they are more likely to benefit electricity utilities, than either the farmers or arresting groundwater depletion. It is therefore in context of these issues, that these energy policy interventions have seen little buy-in from the farmers (Dubash, 2005).

Given the limitation of the changes in energy policy, there is a need to look at the problem from a holistic perspective. Energy and groundwater are inputs to support agriculture development and improving farm productivity. In fact, choice of crops by farmers are not determined alone by the quality and economic cost of different inputs such as electricity, but, the economic returns, market demand for commodities, and market linkages are dominant factors. The debate on water – energy nexus would remain incomplete and lead to inconclusive solutions, without looking at the role of agriculture sector policies.

Adding the agriculture component to the nexus as shown in Fig.1 modifies the water-energy nexus. The schematic diagram shows that there is a vicious cycle operating within-water, energy, and agriculture sectors - creating a nexus. In the absence of effective groundwater legislation to control over-exploitation of groundwater, and under the favorable condition of agriculture policy, which emphasizes on production of food grains through procurement support, there is excessive dependence on water intensive crops leading to depleting groundwater levels and lack of crop diversification. Perverse incentives provided as part of the energy policy coupled with poor quality and un-reliable electricity supply has resulted in long hours of pumping and leading to wastage of both energy as well as groundwater. Implementation of policies in the agriculture and energy sectors, have resulted in misguided targeting, as benefits of the agriculture subsidies are captured by agriculturally prosperous states and benefits of electricity subsidy are mostly retained by rich farmers, instead of poor states and small/marginal farmers.

Although Figure 1 shows the internal vicious cycles between agriculture, water and energy sectors, it does not show the coping mechanisms that farmers adopt in light of inefficient power supply. Rapid growth in groundwater wells is largely because of unreliable power supply. When power fails, the additional wells would have pumped enough to meet the requirements. When pump fails, the additional wells would be used to fill in. Surveys in Andhra Pradesh and Haryana also showed that most of the large and medium farmers had more than two wells per farmer. These are the ones that have the capacity to invest in additional wells and benefit from energy subsidies. The coping mechanisms adopted by the farmers add to increased pressures on both energy and water (Sharma et.al, 2005).

Groundwater

Groundwater irrigation developed towards early 1960s in India, and expanded rapidly after 1969 with the expansion of grid electricity to rural areas. At present, groundwater supplies water to 70% of the irrigated area (Shah et al., 2003). Over the last two decades, 84% of the total addition to the net irrigated area came from groundwater, and only 16% from canals (Figure 2). As it can be seen from the Figure 2, the net irrigated area by groundwater is about twice the area irrigated by the canals.

The current dependence on groundwater irrigation started as a viable alternate option largely due to certain critical changes that took place in the Indian agriculture and irrigation sectors. Surface irrigation sources such as canals and tanks required massive public investment and complex institutional set-up. Over the years public investments in irrigation infrastructure has declined and simultaneously the surface irrigation source suffer from poor maintenance leading to deterioration in quality and inadequacy of water supplies.

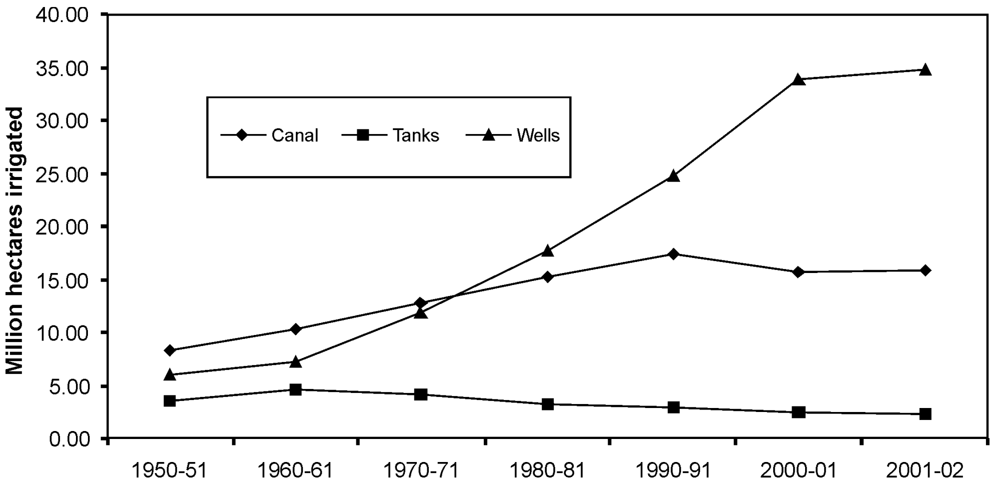

Figure 2. Source-wise irrigation development in India

With India's demand for food security becoming the primary objective of agriculture development, the demand for groundwater irrigation increased. Groundwater irrigation was also considered as a viable technical option to reduce water logging and salinity in certain areas of river basins. For the farmers, groundwater provided flexible option of applying right quantities of water when needed. Groundwater irrigation received further fillip due to increased availability of irrigation pump sets at affordable prices and ease in access to subsidized credit.

Groundwater exploitation in India has contributed to irrigation, poverty reduction, and rural development benefits. However, its utilization pattern and heavy dependence have raised sustainability concerns. Groundwater estimates indicate that more than 9% of the administrative blocks/watersheds/*talukas* are over-exploited, and nearly 5% of them are in critical stage (Romani, 2005). These estimates are based on assessment conducted around 1999. The situation has aggravated since then. For example in Karnataka, the 1999 estimates identified a Doddaballapura *taluka* as "safe" and only parts of the *taluka* were semi-critical (GoK, 2004). However, the recent assessment by the state government department shows that the entire *taluka* has now been classified as "critical"(Venugopal, 2005). The change in the availability of groundwater in this area has been largely due to increase in number of bore wells, increase in depth of bore wells, and poor maintenance of tanks. Anecdotal evidence from the area also suggests that the well failure rate is extremely high, and existing bore wells have started to dry.

Agriculture

Agriculture has been the mainstay of the economy and its growth is pre-requisite for economic and social development of the Indian economy. As noted earlier, agriculture sector accounts for 22% of the GDP, but at the same time, it supports livelihoods of 58% of the population. The Xth Five Year Plan (FYP) has targeted an average annual growth rate of the agriculture sector at 4 per cent

(Planning Commission, 2002b). However, monsoon plays a critical role in the growth rate of the sector. Severe drought in 2002 resulted in negative (-7.0 per cent) growth rate, as deficient rainfall significantly affects *Kharif* (rainy season) food grain production (GoI, 2005a).

Post independence growth of agriculture owes much to the conscious and proactive government policy to promote agricultural productivity and overall development. These could be largely ascribed to measures such as public investments in irrigation, rural electrification, research and development and transfer of knowledge to field to improve crop productivity, development of credit networks and extension services, guaranteed support prices for outputs and subsidized inputs. Annual growth rate of 2.7% for all crops achieved during 1949-1995 was considerably higher than insignificant growth of 0.3% per annum registered during the first half of the century. Accordingly, food grain production has grown from 50.8 million tonnes in 1950-51 to about 212 million tonnes in 2001-02.

However, in striving to achieve food security, the basic principle of rational pricing and sustainable management of natural resources were neglected in India. The magnitude of un-recovered costs on subsidized inputs has been rising at a much faster rate than public investment in the sector. Apart from rising input subsidies, subsidy provided by the government as output subsidy in the form of food subsidy has also been increasing and contributing to the rising subsidy bill for the government. Food subsidy in India comprises of subsidies to farmers through support price and purchase operation of the Food Corporation of India (FCI), consumer subsidies through the public distribution system, and subsidies to FCI to cover all its costs. Food subsidies are mainly on account of food grains - paddy and wheat - both being water intensive crops and rely on groundwater.

Food subsidy, especially the minimum support price (MSP) has asserted in improving food security through affordable prices for the consumers and incentives to the farmers in form of assured market and thus keep food grains production at a comfortable level. However, these policy measures have also created a lock-in situation, where food grains production dominates and domestic production of other cereal crops and oil seeds have suffered because of food security. Analyzing the food subsidy bills in India for the period between 1990-91 and 2003-04, shows a ten times increase in the food subsidy (Table 1). In 1990-91, the food subsidy was Rs 245 billion (1 USD ~ INR 45) and it increased to Rs. 2580 billion in 2003-04. In fact, after 1994-95, the annual growth in the food subsidy bill has registered a growth, due to increase in MSP and open-ended procurement. Food subsidy is further increased by the low off-take of food grains for distribution and build-up stocks.

Higher food subsidy bill in the last five years has been on the account of open-ended procurement policy with no upper bounds on procurement levels. Under this procurement scheme, the government buys whatever is offered to it at the 'going' MSP. Analyzing the food subsidies in India indicates that a large part of the recent problems arise from the relatively high MSPs (Table 2). Not only the MSP is higher, it is also at levels higher than the price recommended by the Commission on Agricultural Costs and Prices (CACP). The declared MSP has had several negative fallouts. Significant from the water-energy nexus perspective, is the fact that the exclusive attention to wheat and rice has distorted the cropping pattern of

Table 1. Growth of food subsidies in India

Year	Food subsidy (Rs.,billion)	Annual growth (%)
1990/91	245.0	—
1991/92	285.0	16.33
1992/93	280.0	-1.75
1993/94	553.7	97.75
1994/95	510.0	-7.89
1995/96	537.7	5.43
1996/97	606.6	12.81
1997/98	790.0	30.23
1998/99	910.0	15.19
1999/2000	943.4	3.67
2000/01	1206.0	27.84
2001/02	1749.9	45.10
2002/03	2417.6	38.16
2003/04	2580.0	6.72

Source: (Ministry of Finance, 2004).

Table 2. Minimum support price(MSP, Rs. per 100 kg) of wheat and paddy

Crop Year	Paddy (Common)		Wheat	
	MSP	% Change	MSP	% Change
1990-91	205		225	
1995-96	360	5.9	380	5.6
1996-97	380	5.6	475	25.0
1997-98	415	9.2	510	7.4
1998-99	440	6.0	550	7.8
1999-00	490	11.4	580	5.5
2000-01	510	4.1	610	5.2
2001-02	530	3.9	620	1.6
2002-03	530	—	620	—
2003-04	550	3.8	630	1.6
2004-05	560	1.8	640	1.6

Source: (Ministry of Finance, 2004; GoI, 2005b).

farmers in the favor of these two food grains alone. The higher water intensity of these two crops in turn has had adverse environmental impacts.

The other negative impact of the MSP is the inequitable distribution of subsidies due to concentration of procurement in just two food grains and selected states. In 2003-04, nearly 95% of the wheat was procured from Punjab, Haryana and part of Uttar Pradesh. Similarly, nearly half of the paddy procurement was from the states of Haryana and Punjab, followed by Andhra Pradesh and Chattisgarh. Not only farmers in these selected states draw the benefits of the subsidies, within these states the large farmers, leaving out small and marginal farmers, mostly enjoy these benefits. Study in Andhra Pradesh has shown that farmers, notably small and marginal, face several hurdles in realizing the MSPs offered by the government.

In summary, food subsidies have not only resulted in being mis-directed and leading to wastage of subsidies, they are responsible for excessive dependence on two food grains – paddy and wheat. This has not only affected the cropping pattern, it has also resulted in over-exploitation of groundwater.

The Energy Angle

Improving access to electricity for social and economic development in the rural areas has been the mainstay of the energy policy in India. Energisation of irrigation pump sets was integral to the rural electrification program with the objective of creating economic opportunities in the agriculture sector along with creating agro-processing units. At the time of independence, there were approximately 6500 irrigation pump sets. In the interim period of 1966-69, between the IVth and the Vth FYPs, about one million pump sets were installed. However, after 1969, there has been an exponential growth in number of energized pump sets (Figure 3). As it can be seen from Figure 3, after 1969, the number of energized pump sets has substantially increased during each plan period. This was possible due to expansion of grid electricity in the rural areas, mostly on the back of multi-purpose irrigation projects, easy availability of pump sets and affordable drilling services in the market, access to subsidized credit, for realizing potential of groundwater for irrigation. The trigger point was the consecutive years of drought between 1966-68, which changed the face of Indian agriculture, irrigation, and role of electricity in supporting irrigation and agriculture for attaining food security.

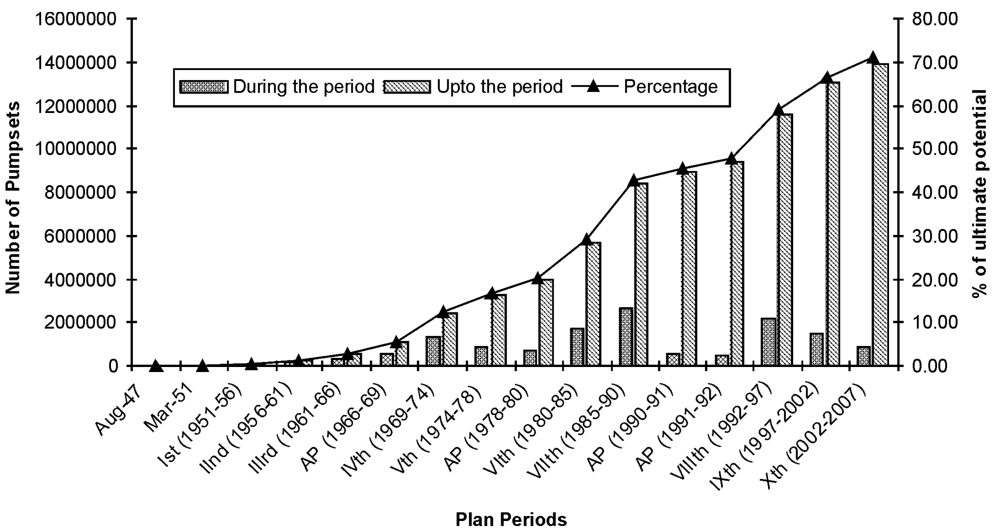

Figure 3. Progress in pump set energization in India 1947-2003 (Source: Sinha (2005)

As it can be seen from Figure 3, 70% of the groundwater potential has already been utilized. Groundwater estimates based on the available resources, indicate that approximately 19 million pump sets can be installed in India. The decline in pace of pump set energization in the last two Five Year Plans is largely due to saturation in most of the agriculture prosperous states, denial of new pump-set connections and subsidized credit in the 'over-exploited' or 'critical' administrative units. In the states such as those in the eastern India, where high potential for groundwater exploitation is possible, then these states are affected by low density of rural electricity grid, poor availability of electricity supply, high incidence of poverty making access to individual ownership of pump set difficult, and these problems are further complicated by bureaucratic inefficiencies in these states.

The widespread increase in utilization of groundwater from 1970s onwards was supported by incentives from the state electricity utilities through provision of subsidized tariff. While 1970s were the peak period for rapid increase in groundwater irrigation, two policy interventions in the energy sector during this period, resulted in their over-exploitation in coming years. One intervention was in the form of change in the billing of agriculture consumers. Agriculture consumers were billed based on energy used as per the energy meter. The billing was changed to load-based tariff (per horsepower [hp]) of the installed pump set capacity. Utilities felt that the change was necessitated to reduce the transaction cost involved in meter reading and bill distribution to the thousands of scattered pump set users in the rural areas. The negative implication of such a move resulted in under-reporting of pump set load used by the farmers, contributing to commercial losses for the electricity utilities.

Second policy intervention came from the government as part of larger political populism. Under pressure from rising farmer's movements in parts of southern Indian states, followed by similar movements in northern India, state governments introduced highly subsidized tariff and subsequently many states offered free electricity for the agriculture sector. Free electricity was introduced in Andhra Pradesh towards the end of 1970s and was followed by Tamil Nadu and Punjab. This political populism soon spread to other neighboring states.

The combined effect of these policy intervention resulted in poor performance of state electricity utilities, which over a period due to under-recoveries, became financially insolvent. While the agriculture sector share in total electricity sales increased, revenue realization remained extremely low. As it can be seen from Figure 4, during the period of 1994-95 and 2001-02, total sales of electricity to the agriculture sector was more than 30%, but revenue realization was less than 5% (Planning Commission, 2002a). The high commercial losses meant that the investment by the utilities in electricity distribution infrastructure declined over the years. As a result quality of power supply was characterized by low voltage and frequent outages and reliability of supply further deteriorated. At the same time power supply was scheduled during off-peak demands, therefore resulting in supply during night time. Farmers coping mechanism to counter low voltage power supply and frequent interruption during scheduled supply was to use phase splitters to run pump sets from single-phase power supply. To counter the nighttime power supply and unscheduled supply, farmers adopted auto-switch to run pump sets. Implication of such pump set utilization pattern negatively affected groundwater utilization.

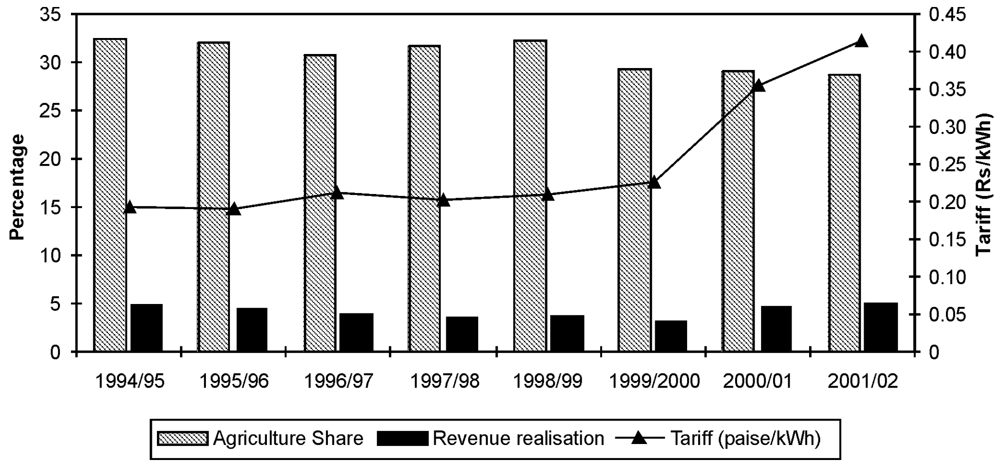

Figure 4. Electricity for agriculture consumers in India – agriculture share (%), revenue realization (%) and changes in average agriculture tariff 1994/95-2001/02 (Source: Planning Commission 2002(a)

Not only these policy interventions created unfavorable utilization of groundwater, they also contributed towards rising subsidy bills. Cumulative subsidies provided by all states for agricultural consumers increased from Rs. 593.8 billion in 1991-92, when energy sector reforms were started, to Rs. 2380.6 billion in 2004-05 (Table 3). This increase in subsidies has been despite the adoption of minimum tariff of Rs. 0.50 per unit under the common minimum plan for power sector reforms. The rising subsidy bills have largely been on the account of political interference in pricing of electricity for agricultural consumers, and it has been in the form of either free electricity or waiver of electricity dues.

Table 3. Growth of electricity subsidies for agricultural consumers in India

Year	Subsidy (Rs. billion)	Annual growth (%)
1991-92	593.8	
1992-93	733.5	23.53
1993-94	896.6	22.24
1994-95	1094.1	22.03
1995-96	1360.6	24.36
1996-97	1558.6	14.55
1997-98	1902.1	22.04
1998-99	2247.3	18.15
1999-00	2417.8	7.59
2000-01	2407.4	-0.43
2001-02	2401.3	-0.25
2002-03	2184.5	-9.03
2003-04	2334.6	6.87
2004-05	2380.6	1.97
2005-06	2537.7	6.60

Source: (GoI, 2002; Planning Commission, 2002a; GoI, 2004; GoI, 2005a).

Political populism in the energy sector can be classified into two categories – one, pertains to provision of free electricity, a policy which was followed by states such as Punjab, Madhya Pradesh and Tamil Nadu and were reintroduced by states such as Andhra Pradesh and Tamil Nadu after 2004 state assembly elections. Maharashtra also provided free electricity for short period in wake of 2004 state assembly elections and withdrew the scheme within six months of returning to power. Punjab, which gave free power in 2002, also withdrew in six months, but recently in 2005, the state government has reintroduced free power in view of forthcoming state election. Second, measure is in form of waiver of electricity dues, a policy that has been continuously followed by many states and in recent years, states such as Madhya Pradesh, Karnataka, and Maharashtra in 2004 gave waiver of electricity dues just before state assembly elections. Haryana offered waiver of arrears with a rider that with regular payment of 10 bi-monthly bills, arrears shall be reduced by 10% with each payment. While waiver of arrears is not same as providing free power, but instead is an interim measure of providing relief to farmers. However, this has resulted in creating a non-payment behavioral pattern by the farmers, who expect another round of waiver to come in future. For example, empirical evidence from Karnataka shows that farmers have stopped paying electricity bills after a waiver was announced before state assembly elections in 2004.

Discussion

Analysing the scenarios of groundwater, agriculture, and energy sectors and the implications of the policies on groundwater over-exploitation, policy and program intervention in the water sector needs to be supported by appropriate policies of the energy and agriculture sector. Direct management of groundwater suffers largely due to lack of legislative instruments including low opportunities for effective implementation of legislative controls (even in states where such legislations are existing), development of groundwater through right of capture, political sensitivity associated with its use for agriculture, food security and livelihoods, and the fact that much of the groundwater development actually takes place through private capital investments of the farmers. Even in states such as Andhra Pradesh, which enacted an Andhra Pradesh Water, Land, Trees Act, has run into institutional barriers and lack of teeth to restrict over-exploitation of groundwater (Narayana et al., 2005). Given this broader context of the groundwater, specific intervention can be focused on recharging the aquifers by managing run-off water from surface irrigation sources and rainfall. These interventions can provide positive benefits, however, the rate of recharge varies and rate of extraction is influenced by crop choice and density of pump sets. Energy sector policies and agriculture policies have to support groundwater interventions. Anecdotal evidence from watershed management in Madhya Pradesh showed that once the three-year restriction on digging new bore wells was removed, irrigation pump sets mushroomed. Even under other watershed management programs, benefits of groundwater recharge efforts by the community upstream were captured by few influential farmers downstream (Sharma et al., 2005).

Energy Options

The current approach in the energy sector has focused on technical and financial fixes to the problems. However, energy policies are concerned until the meter side of the pump set. Metering is the most debated aspect, as energy sector reforms proponents have argued that metering may not only reduce distribution and commercial losses for the utilities, but also induce efficient pumping and adoption of efficient pump sets by the farmers (Padmanabhan, 2001). The latter is assuming that farmer's would be rational in their approach, and is not likely to take place unless an overall change is brought in the distribution of electricity supply – quality, reliability, and time of supply (Reddy, 2000). Benefits of metering will be largely drawn by the electricity utilities, as it will improve accountability in the sector, however, there is little buy-in from the farmers. Farmers look at metering with distrust, as they expect that the otherwise flat tariff would increase in near future. Farmer's opposition to metering also stems from the fact that metering would not allow them to pilfer by under reporting pump capacity.

Pricing of electricity closer to the cost of supply is another common prescription. Appropriate tariff is the most prudent option, however, electricity pricing for the agriculture sector follows political logic rather than sound economic principles. The common quote from an influential politician states that " Pricing is not just a matter of people's willingness to pay. It's also a matter of politicians' willingness to charge". At the same time, there are other sets of arguments related to pricing of electricity. Electricity supplies to farmers are in fact, off-peak and highly unreliable, and thus does not cost the electricity utilities even the average cost of supply (Bhatia, 2005). At a larger policy level, since electricity pricing are linked to political outcomes, tariff rationalization is not likely to be achieved in many states. The problem is not such much of appropriate tariff, but the inability of the utilities to do collection. In the recent past, there has been lot of outcry related to provision of free power. Free power sop runs contrary to the Electricity Act, 2003, which prescribes a gradual phasing out of cross-subsidies. However, there are several states which give waiver of electricity dues, and in the absence of revenue collection, electricity supply virtually becomes free. For example in Karnataka, where the utilities are not collecting any revenue from agricultural consumers, and at the same time the farmer are unwilling to pay and hoping for waiver of dues.

In this context, three options of energy side need to be explored further:

- The first is the analysis of the scheme introduced by the State Government in Haryana in 2005. Instead of giving a one-time waiver of electricity dues, the government introduced an "Arrear Waiver Scheme." As per the scheme, 10% of the arrear would be written off with the continuous payment of each of the next ten electricity bills on a two-month cycle. If the farmers miss any of the current payments, the scheme will start all over again. Preliminary observations indicate that scheme has been quite successful as more than 90% of the farmers in Bhiwani and Jind districts – districts with highest incidences of default - have utilized the scheme.
- The second option pertains to adopting a different system for setting electricity tariff for groundwater utilization. At present, the State Electricity Regulatory Commissions (SERCs) or State Electricity Boards (SEBs) sets tariff (per HP or

per unit) for different consumers across the state and based on pooled average cost of supply. There is no differentiation in the tariff for different regions. Instead of this pooled average cost of supply, electricity tariff could be fixed based on the groundwater classification as over-exploited, critical and safe. This will not only bring two sectors to work together, it will also provide some accountability towards how groundwater has to be utilized. As part of the distribution reforms in the electricity sector, multiple distribution utilities either have been formed or are in the process, which makes it possible to have groundwater classification based electricity tariff. Regions that are classified as over-exploited can have higher electricity tariff (flat or metered), when compared to regions, which are classified as safe. High electricity tariff rate would act as a deterrent for farmers to grow water intensive crops in over-exploited and critical areas. In other terms, higher tariff for the over-exploited and critical areas would be equivalent to an environmental cess, which the farmers in such regions would have to pay to utilize groundwater. However, implementing such tariff system requires maturity to think out of the hat by the SERCs/SEBs, which set the tariff. This will also require a political vision to introduce such differential tariff system.

- The third option relates to matching energy supply with the irrigation needs of the farmers. Crop water needs are generally not linear in nature but follow a pattern closely dictated by crop growth patterns with high water/ energy requirements during planting and high vegetative growth (Sharma et. al, 2005). At the core of the nexus, is the mismatch between irrigation needs and energy availability. Power supply is good and reliable, when the irrigation needs of the farmers are low, and of inferior quality and in short supply when the irrigation needs are higher. When the irrigation needs are higher and power supply is unreliable, farmers are frustrated and opt for options such as excessive pumping of groundwater, power pilferage and default. These pumping patterns not only stress the electricity distribution infrastructure, but also increase commercial losses for the utilities. Matching energy supply with irrigation needs of the farmers would result in a win-win scenario, as farmers would be happy and the volume of subsidy would be controlled. However, this would require significant work at the electricity feeder level by developing local intelligence mechanisms. Shah et al., (2003) also suggested 'intelligent power supply' in which energy supply pattern is matched with crop water needs.

Agriculture Options

While managing input subsidies such as those provided by electricity can result in, to some extent, in efficient utilization of groundwater, but a more direct approach would come through policy interventions from the agriculture sector. There are two inter-linked policy issues, which can have direct bearing on groundwater utilization as well as equitable distribution of food and energy subsidies. First, policy issue deals with the restructuring of the MSP mostly targeted to paddy and wheat. Second, policy issue is the procurement policy for the food grains, which is inter-linked to MSP. Both these policy options have to be reviewed and implemented concurrently.

- As argued under the agriculture sector, MSP associated with paddy and wheat accounts for bulk of the food subsidy bill. In the last five years, the MSP prices for paddy and wheat have increased marginally, but open-ended procurement norms distort subsidy allocation, as well as encouraging paddy and wheat cultivation in states, which are increasingly becoming water scarce regions. The government needs to intervene either by freezing the MSP or by introducing a time bound phase out of the MSP. This is likely to trigger cropping pattern shift by the farmers, if the economic returns are no longer attractive. From a policy perspective, this option again has political implications. MSP restructuring would be effective, if it is accompanied by providing incentives for alternate crops, which provide at least similar economic returns as those from paddy and wheat. It would also require government to strengthen MSP as well as support them with market access in either domestic markets or international trade for other cereal crops and oilseeds.
- Restructuring the procurement norms for food grains is inter-linked with the restructuring of MSP. The current procurement policy is open ended, as there is no upper limit set. This has distorted procurement from states, which are increasingly becoming water scarce (Punjab, Haryana, western Uttar Pradesh). In the last two years, FCI, has made some changes in procurement and it is now focused on eastern Indian states for procuring paddy (GoI, 2005a). However, they account for approximately 10% of the total procurement. In order to restructure the procurement policy, the government might put upper ceiling of procurement. In other words, the government needs to introduce fixed quota for each food grain to be procured and gradually reduce the quota from states such as Punjab and Haryana. Imposing such quota limit is likely to influence farmer's decision to undertake cropping pattern change. However, the government needs to introduce safeguards through incentive and market linkages to grow other crops.

Conclusions

This paper has discussed role of indirect options pertaining to energy and agriculture policies simultaneously for efficient utilization of groundwater. While some of these policy interventions are already under review and implementation, they require rigorous public debate to find the appropriate balance. Given the groundwater realities in India, and likely future scenario, it is critical to understand, that no single policy intervention can solve the problem. Energy policies can play a role, but their implementation is fraught with political compulsions and their inherent limitations as a solution in sectors other than energy. Thus, the energy policies will be able to find solutions for the energy side of the nexus; the energy policies on their own will have little to offer for the groundwater.

Farmer's choice of crop is certainly influenced by input subsidies, but they are influenced by assured prices and market, both of which are provided by the government's food subsidy and procurement policies. Procurement policy and MSP needs to be revamped, not just from reducing fiscal burden on the exchequer and from equity perspective, but long term environmental benefits and livelihoods security that can be achieved from efficient utilization of groundwater. Both the indirect policies of energy and agriculture sector needs to be concurrently approached to bring diversification of agriculture and therefore arresting groundwater depletion, and safeguarding livelihoods and food security.

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Integrating Science into Groundwater Management Decisions

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Abstract

Groundwater development has seen an unprecedented growth in many parts of the world during the last couple of decades. Especially in populous Asian countries like India and China, exponential growth rates, in terms of number of wells and estimated accumulated pumping volumes, give an impression of an explosion rather than a steady and controlled evolution.

This paper examines the general distinct features of groundwater that poses both the merits for its rapid utilization potential as well as the obstacles for its sustainable management. It looks at the key challenges to groundwater management that reflect and respond to the various stages of development and some misconceptions that tend to hamper an effective approach to groundwater management. The concepts of 'safe' or 'sustainable' yield and 'groundwater overexploitation' are particularly interesting as they have been inscribed in the contemporary groundwater vocabulary, and while they may be valuable in environmental debates they bear no scientific definition, let alone guidelines for thresholds on sustainable groundwater exploitation. The paper investigates the roles of groundwater scientists and managers in an attempt to identify the means to unlocking the gap that is often perceived between these two parts in the collective development of practical management solutions to groundwater degradation. Ways forward are suggested, with particular focus on the linkage between assessment of groundwater potential and decision-making on groundwater development in India.

Introduction

Traditionally, the focus of water managers has been on surface water, except maybe in cases of extreme aridity and/or non-mountainous areas. This can be explained by the fact that surface water is immediately accessible and tangible whereas groundwater is concealed and not directly within reach. On the other hand, distinctive features of groundwater, like its prevalence and reliability in supply and quality (Table1), have over the last quarter century proven to be major drivers for its utilization in widespread small scale irrigation farming in developing countries (Shah, 2004). However, the same inherent characteristics of groundwater, its invisibility and prevalence, also give rise to major challenges faced by groundwater managers. Trying to cope with an excessive number of individual users over vast areas and book keeping their use is almost impossible, even in a developed country setting. Add to this the distinct general features of groundwater of slow flow rates, long residence times and long response times to external impacts, like excessive pumping, chemical spills or non-point sources of pollution, it becomes clear that groundwater management is not a straightforward task.

Table 1. Comparative features of groundwater and surface water resources

Feature	Groundwater resources and aquifers	Surface water resources and reservoirs
Hydrological characteristics		
Storage volume	Very large	Small to moderate
Resource areas	Relatively unrestricted	Restricted to water bodies
Flow velocities	Very low	Moderate to high
Residence times	Decades/centuries	Weeks/months
Drought propensity	Generally low	Generally high
Evaporation losses	Low and localized	High for reservoirs
Resource evaluation	High cost and significant uncertainty	Lower cost and often less uncertainty
Abstraction impacts	Delayed and dispersed	Immediate
Natural quality	Generally (but not always) high	Variable
Pollution vulnerability	Variable natural protection	Largely unprotected
Pollution persistence	Often extreme	Mainly transitory
Socio-economic factors		
Public perception	Mythical, unaware	Aesthetic, aware
Development cost	Generally modest	Often high
Development risk	Less than often perceived	More than often assumed
Style of development	Mixed public and private	Largely public

Source: Tuinhof et al., 2003.

As a general rule, groundwater development in many Asian countries has been left to the private initiative. When groundwater exploitation on a wider scale took off in India in the 1970s it was driven primarily by private, small-scale farmers who saw the possibilities in increased income from farming supported by groundwater irrigation, which was made possible and lucrative by government funds, grants and subsidies on drilling, pumping equipment and energy required to start and sustain the business. Similar developments have been seen in China, Pakistan and other Asian countries, though local differences occur and the case of India is extreme and therefore worth focusing on (Shah et al., 2003).

When groundwater exploitation is approaching levels that appear to have excess negative impacts to society, which is the case in some areas of India, the need for response becomes evident. Also, it becomes clear that a relevant, necessary and adequate response cannot solely be based on, and expected from, the same private initiative that drove it. A reactive, and preferably a pro-active, role from the overall authorities responsible for water development and use is required.

Key Challenges for Groundwater Resources Management

Groundwater resources management deals with balancing the increasing demands of water and land users with the long-term maintenance of a complex natural resource (in terms of quantity, quality and surface water interactions).

Calls for groundwater management do not usually arise until a decline in well yields and/or quality affects one of the stakeholder groups. If further uncontrolled pumping or pollution is allowed, a 'vicious circle' may develop (Fig. 1) and overall damage to the resource may result. All of these effects can be short-term and reversible or long-term and quasi-irreversible (such as aquifer saline intrusion and land subsidence).

To transform this 'vicious circle' into a 'virtuous circle' it is essential to recognize that managing groundwater is as much about managing people (water and land users) as it is about managing water (aquifer resources). Or, in other words, that the socio-economic dimension (demand-side management) is as important as the hydro-geological dimension (supply-side management) and integration of both is required.

Key requirements for groundwater management are the recognition and understanding of:

- The characteristics of aquifer systems and their specific susceptibilities to negative impacts under abstraction and contamination stress.
- The interactions between groundwater and surface water, such as abstraction effects on river base flow and wetlands, and groundwater recharge effects (due to surface-water modifications).
- Operational monitoring as a vital tool to develop the information and understanding needed for effective resource management.

Furthermore, it is essential to bear in mind that:

- Social development goals and policies greatly influence water use, especially where agricultural irrigation and food production are concerned, thus management can only be fully effective if cross-sectoral coordination occurs
- Regulatory interventions (such as water rights or permits) and economic tools (such as abstraction tariffs and tradable water rights) become more effective if they are not only encoded in water law but implemented with a high level of user participation.
- Regulatory provisions should not go beyond government capacity to enforce and user capacity to comply.
- The development of an effective and sustainable approach to management will always require involvement of the main stakeholders.
- Proper groundwater management requires awareness and capacity at various levels of society, from local level users to central decision makers.
- Proper groundwater management requires the integration of science into management decisions.

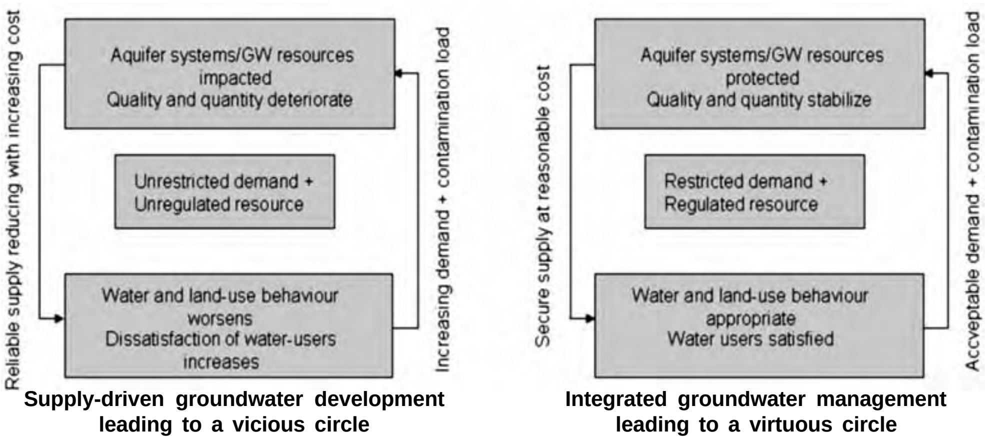


Figure 1. Supply-driven versus integrated groundwater management (Tuinhof et al., 2003)

- Management of groundwater requires integrated approaches that are balancing the needs of the poor and the environment with economic development goals.
- Hydrogeologic and socio-economic conditions tend to be location-specific and thus no simple blueprint for integrated groundwater management can be provided.
- International/inter-state cooperation on cross-boundary groundwater problems is essential for long-term sustainable groundwater management.
- International cooperation and knowledge sharing should play a significant role in facilitating development of sustainable groundwater management.

Stages of Groundwater Development and Management

Not-withstanding the hydrogeologic and socio-economic differences encountered in various countries, a typical evolution of groundwater development (Fig. 2) can be portrayed to illustrate the various levels of development and the phases that follow from a situation where the exploitation of groundwater is minimal to a situation where excessive abstraction and contamination takes place, through to a more balanced and controlled situation based on sound management.

The various stages of development require different types of responses, and by choosing the right level and type of response, corresponding to the actual level of development, the unstable situation, depicted as situation 3 in Fig.2, can be avoided (Tuinhof et al., 2003). Figure 2 illustrates the increasing need for integrated management as groundwater exploitation increases. The development is not only associated with increasing costs as more supply augmentation and management measures are required, but also in increasing complexity as the solutions and assessments become more and more integrated, the potential impacts are more wide-reaching, and the balances in society more precarious. This is exactly why integrated groundwater management calls for the collaboration between the managers and the researchers.

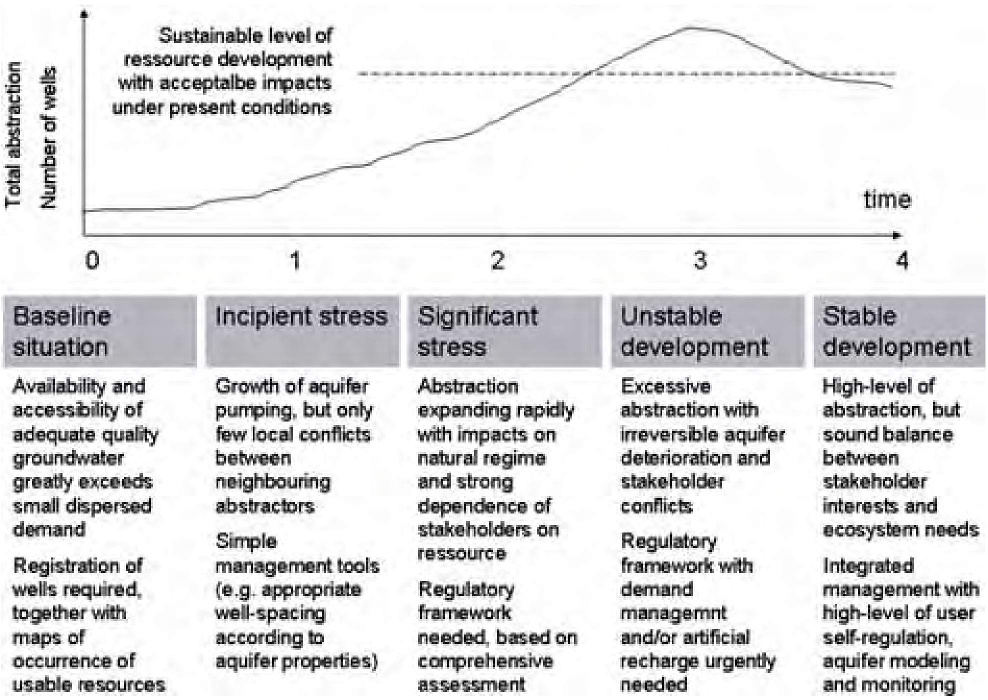


Figure 2. Stages of groundwater resource development in a major aquifer and their corresponding management needs

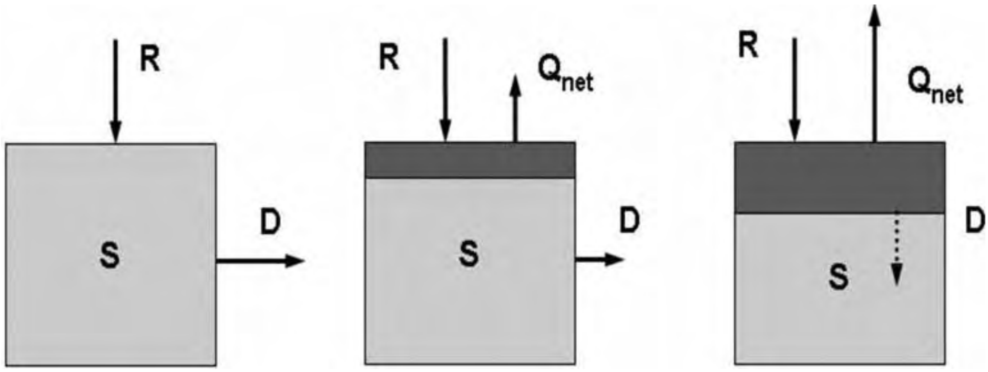
Some General Misconceptions of Groundwater

'Safe' or 'Sustainable' Yield

Estimation of contemporary aquifer recharge is fundamental in sustainable groundwater resources development. Current long-term average rate of aquifer recharge will indicate the volume of water entering the system and being available for storage and later discharge and use.

When evaluating effects of groundwater abstraction on the resource availability and estimating an acceptable level of abstraction, the fundamental tool is the water balance stating that water that enters groundwater will either be discharged (through a stream, lake or spring) or may be kept in (temporary) storage. Any effective reduction in recharge to the groundwater (from less rainfall or groundwater abstraction) will mean a reduction in discharge and/or storage (Fig. 3).

The average recharge is often, erroneously, considered the 'safe' or 'sustainable' yield, assuming that this is the amount of water that can be pumped from the groundwater without long-term consequences. However, this notion disregards the need to maintain aquifer discharge or water level in downstream freshwater systems or aquatic/terrestrial ecosystems or to suppress coastal salt-water intrusion.



Natural conditions	Stable groundwater punping	Unsustainable condition
Averaged over long-term R=D and S is constant	Qnet is equivalent to reduction in D and S	Qnet is greater than R, D reduced to O and S decreases continuosly

Figure 3. Conceptual effects of abstraction on the groundwater resource balance (from Foster et al., 2003)

'Groundwater Overexploitation' and Continuously Declining Groundwater Levels

The term 'groundwater overexploitation' has become everyday vocabulary in water management as well as the media. However, it fails to bear a rigorous scientific definition. Some regard an aquifer as being overexploited when its groundwater levels show evidence of 'continuous long-term' decline. But this is also a rather ambiguous measure or criteria for identifying problems of excessive pumping. When are the declines statistically significant, how many years to average over, are they due to erratic or systematic changes in rainfall and will they continue?

The fact is that all groundwater abstraction will lead to drawdown, but whether the declines will persist (ref. c in Fig. 3) can often not be assessed over a shorter period because the flow processes in groundwater are slow and it may take years for a new equilibrium to be established (ref. b in Fig. 3). Not-withstanding this, falling groundwater levels in areas where effects are obviously impacting local stakeholders negatively, are probably one of the best indicators of the need to intensify assessment of impacts and devise appropriate guiding limits on abstraction.

Another measure of 'overexploitation' is taken to be that abstraction is greater than the long-term average rate of groundwater recharge. However, due to the uncertainty of groundwater recharge mechanisms and methodological difficulties in estimating it this is usually a rather unworkable approach.

In practice, when speaking of aquifer overexploitation we are invariably much more concerned about the consequences of intensive groundwater abstraction than in its absolute level or recharge rate. Thus the most appropriate definition is probably an economic one: that the **'overall cost of the negative impacts of groundwater exploitation exceeds the net benefits of groundwater use',** but impacts can be equally difficult to assess and to cost.

However, the term groundwater overexploitation should not be dismissed altogether, despite lack of precision because it conveys a clear message to the public and the politicians and may bring about the dialogue necessary to define the acceptable negative costs of society associated with intensive use of groundwater.

Rejected Recharge

Another mis-conception refers to the notion that groundwater recharge will increase if the aquifers are drawn down sufficiently before the onset of the rainy season, in order to allow for higher interception in underground reservoirs during the rainy period for later beneficial use in the dry season. The rejected recharge refers to the perceived loss of water storage due to overtopping of the reservoir in the wet season, a concept that is similar to the one applied to surface water reservoirs.

This is an intriguing concept, but several points make the comparison inappropriate. Firstly, if groundwater tables are lowered excessively during the dry season, it may have major downstream impacts on other water users and/or surface water bodies dependent on the discharge from groundwater or the maintenance of a certain water level (ref. b in Fig. 3). Effectively what is obtained is an abstraction of water that was previously available for downstream uses.

Secondly, groundwater recharged during the wet season will not be retained in enclosed reservoirs with a maximum storage capacity like behind surface water dams. Though a reliable resource will be available for abstraction through the dry season, the total absolute amount of available groundwater from recharge will not be increased in the case where groundwater levels have been suppressed to leave room for incoming monsoon recharge.

The only situation where increased pumping in the dry season could be justified is if the water taken out is not consumed (i.e. lost by evapo-transpiration) and it can be brought back into the system without harming the environment and hence allowing it to be reused further downstream.

The last argument for not drawing down the aquifers prior to the wet season is that the system becomes much more vulnerable to drought. If the monsoon rainfall fails the groundwater 'reservoir' will not be replenished to the same extent as without prior drawdown leaving much less buffer in the system to counteract a drought situation.

Pumping is Equal to Loss in Recharge

Often, groundwater abstraction rates and volumes are equated with the loss in groundwater recharge (Q_{pump} equal to decrease in S in Fig.4) and hence held directly responsible for groundwater depletion. However, in groundwater irrigated areas, a significant fraction of irrigation water drawn from groundwater is not utilized for plant growth and returns to the groundwater as recharge, often called return flow. Hence, it is only the fraction of applied water that is actually depleted/consumed through evapo-transpiration that is contributing to the decrease in net recharge and potentially contributing to groundwater level declines (if this amount exceeds the net incoming rainfall and other irrigation sources). A failure to realize this may misinterpret a decrease in pumping as a decrease in groundwater depletion when, in reality, declines persist because the overall evapo-transpiration increases and the return flows are reduced due to water saving technologies.

The critical parameter to focus on is the actual evapo-transpiration (Q_{net}) in comparison to the incoming water, in terms of rain water and imported surface water. If this balance comes out negative depletion is occurring (S in Fig. 4 decreases).

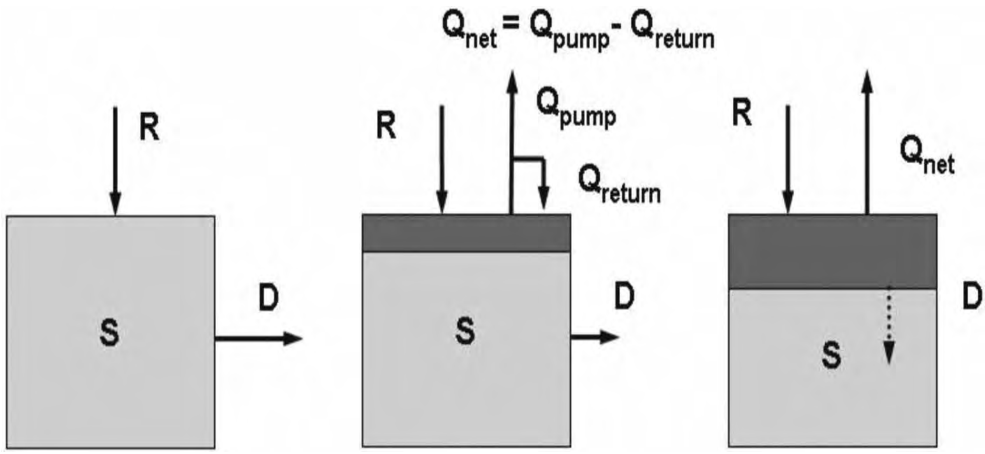


Figure 4. Conceptual effects of abstraction on the groundwater resource balance, considering return flows (from Foster et al., 2003)

Water Savings Free Water for the Environment

An often perceived notion is that with the introduction of water saving technologies (e.g. drip or sprinkler irrigation, green houses), water will be freed for the environment, i.e. if less water is abstracted from groundwater for irrigation, more water will be left in the system to benefit other users, including ecosystems and the environment in general. This perception is directly linked to the previous stated misconception. Applying the same overall rule that only savings in actual evapo-transpiration will improve the overall water balance, drip and sprinkler irrigation will only improve the situation if the overall loss to evapo-transpiration is decreased. This can be the case, without harming crop yields, for these technologies, if the fraction of evapo-transpiration that is attributable to non-plant related evaporation (i.e. direct evaporation from the soil surface) is decreased. So far so good. However, what is often overlooked is the fact that the water savings may encourage the farmers to increase the cropped area with an ensuing increase in evapo-transpiration, which may offset the otherwise obtained water savings.

Secondly, water savings through improved irrigation and cropping technologies may, due to the investment required, lead to the switch to more profitable higher-valued crops (e.g. vegetables, flowers), which require (higher) inputs of agrochemicals (fertilizers and pesticides). In this case, the groundwater balance may be improved quantitatively. However, if the water quality is negatively impacted, the availability of groundwater, with a minimum good quality, is still decreased.

'Excess Runoff' is Available for Artificial Recharge

With groundwater coming under increasing pressure, measures to augment the resource, such as rainwater harvesting and artificial recharge, are often considered the way forward. It is a well-received proposition as it increases existing available and attainable resources without interfering with the demand and use, which has more controversial implications.

The idea is to harness and make utilizable the part of the totally available water resources that is in excess; that is: the fraction that today is not captured and is discharged as 'excess runoff', in rivers. Some overall conditions may, however, make this concept less straightforward, feasible and efficient in addressing the groundwater, and in general the overall water shortage problems.

Firstly, problems of groundwater depletion are directly correlated with the overall water availability in a particular area. Intensive groundwater utilization and concomitant problems are generally much more prevalent in arid and semi-arid climates where the water availability naturally is low. This indicates that only in those areas where rainfall is highly seasonal and leading to 'excess runoff' during part of the year, will there be a potential for harvesting additional groundwater during the rainy season. If river basins are already closing, i.e. rivers discharging only minimal amounts at their outlets, which are not uncommon phenomena today, even for larger rivers (e.g. the Yellow River in China) this overall excess may not be available, at least not on a reliable basis.

Secondly, when evaluating the potential for artificial recharge it is essential to assess the overall impacts in a basin context. Harvesting water for groundwater use in upstream reaches, though on a smaller scale, may appear feasible because of 'excess runoff' in these regions. However, downstream effects, of a multitude of such schemes, in terms of decreased water availability, and quality degradation, such as salinity intrusion, will have to be considered.

As water scarcity and disparity between water-rich and less water-rich regions become more apparent, an inevitable solution seems to be the transfer of water from water-abundant to water-deficient areas. Such solutions are not new, and will most likely occur on a wider scale (both in terms of prevalence, and in size of schemes and distances over which water is transferred). As the potential, and limitations, of rain water harvesting and artificial recharge are explored and realized the further potential for water transfer will most likely be developed.

The Role of Groundwater Scientists and Managers

As groundwater resources come under increasing pressure, allocation between various users, including the environment, becomes increasingly complex and the need for sound approaches based on science becomes progressively more evident (Acreman, 2005). As stated earlier, groundwater resources with its complex and distinct features call for proper technical and scientific knowledge. Adding to this the complexity of the human and socio-economic factors, and the need for integration at many levels (with surface water considerations, sectoral interests, etc.), the challenges are numerous.

Traditionally, and especially in the developing part of the world, a gap is perceived between groundwater managers and scientists. This is explained by differences in traditional roles, driving forces, perspectives and probably also reciprocal misconceptions (Table 3).

Table 3. Traditional differences between scientists and managers

	Scientist	Manager
Perspective	Long-term results	Short-term decisions
Driving force, outer	Peers, theory, funding, data	Public, media, donors legislation
Driving force, inner	Curiosity, explanation	Political influence
Evaluation criteria	Scientific publications	Political support
Working focus	Detail, quantity, facts, comprehensiveness	Integration, quality, opinion, simplicity

While a scientist has the long-term perspective and is driven by his own curiosity and subjected to limitations of data and funding availability and looks at facts and details, the manager is concerned with short-term decisions, the reconciliation of views and the general political scene surrounding management at various levels.

Clearly, there is a need to close the gap, to soften up the traditional roles and to improve the appreciation of the significance of mutual understanding of roles and of communication.

The overall goal is to form a partnership that ensures that decisions are made based on the best available multidisciplinary (technical as well as socio-economic) scientific knowledge. Each partner must be prepared to adopt non-traditional practices to enhance the collaboration. Scientists need to:

- Give direct answers to specific questions.
- Give their opinion concerning questions where no firm scientific facts are available, based on their accumulated knowledge.
- Train themselves in associated disciplines that enable them to contribute to more integrated analysis.
- Present results in a form that can be understood by non-specialists.

Water managers, on the other hand, need to:

- Formulate the questions in a way that lends itself to scientific investigation.
- Accept that some questions cannot be answered by current scientific knowledge and are thus a matter of political judgment.
- Accept that uncertainty exists with respect to the answers obtained through science and that the risks associated with the uncertainty should be reflected in the resources put into reducing the uncertainities.

Assessment of Groundwater Potential and Decision Making on Groundwater Development in India

In the last section of this paper, the specific case of groundwater management in India is explored briefly to exemplify some of the requirements needed and the ways forward. It focuses on the technical assessment of available groundwater resources and its application for political decisions on further groundwater development.

Groundwater recharge and development potential assessment in India is based on the two methods (G.E.C., 1984, 1997):

- Water Level Fluctuation Method
- Rainfall Infiltration Method based on ad-hoc-norms

Basically, the current level, or stage, of groundwater development is determined based on a comparison of the estimated actual recharge with the current groundwater draft. If groundwater draft is higher than the utilizable resource (taken as 85% of the actual recharge), development level is considered higher than 100% and a restriction on further groundwater development is implemented.

Though the method is applied rather systematically and broadly over most parts of India (see Fig. 5), some critical issues need further consideration in order to enhance its accuracy and efficiency:

- The method is based on relatively sparse, uncertain data, crude generalizations, simple empirical classifications and norms, making the method at most relative and indicative, rather than absolute and fully quantitative. The method has been improved by including assessment of temporal trends in groundwater levels.
- Groundwater abstraction rates are still used as the parameter indicating groundwater use though this is associated with significant flaws (see Section 'Pumping is equal to loss in recharge').
- Updating of assessment is infrequent and delayed, making an updated, real-time assessment impossible[1]. This is critical when development of groundwater is occurring at present rates.
- The assessment is not implemented in a management and consultation process, linking scientists, managers and groundwater users, in order to enhance the chance of adoption of control measures against excessive abstraction.

Suggestions for improving the accuracy and management application of the method include:

- Testing the method against rigorous scientific methods in a well-defined pilot area, where additional and more accurate field data can be collected. It is suggested to incorporate remote sensing methods to improve the spatial determination of actual evapo-transpiration and hence the water depletion and the upper limit to groundwater depletion. Biggs (2005) have used this approach in the Krishna basin for overall water balance assessments, and it should be modified for use in focused groundwater assessment studies.
- Extending the existing groundwater monitoring network, especially for monitoring groundwater levels, and intensifying monitoring in areas of suspected groundwater depletion.

[1] Central Groundwater Board has informed that a revised assessment will be published soon (Rana Chatterjee, 2005).

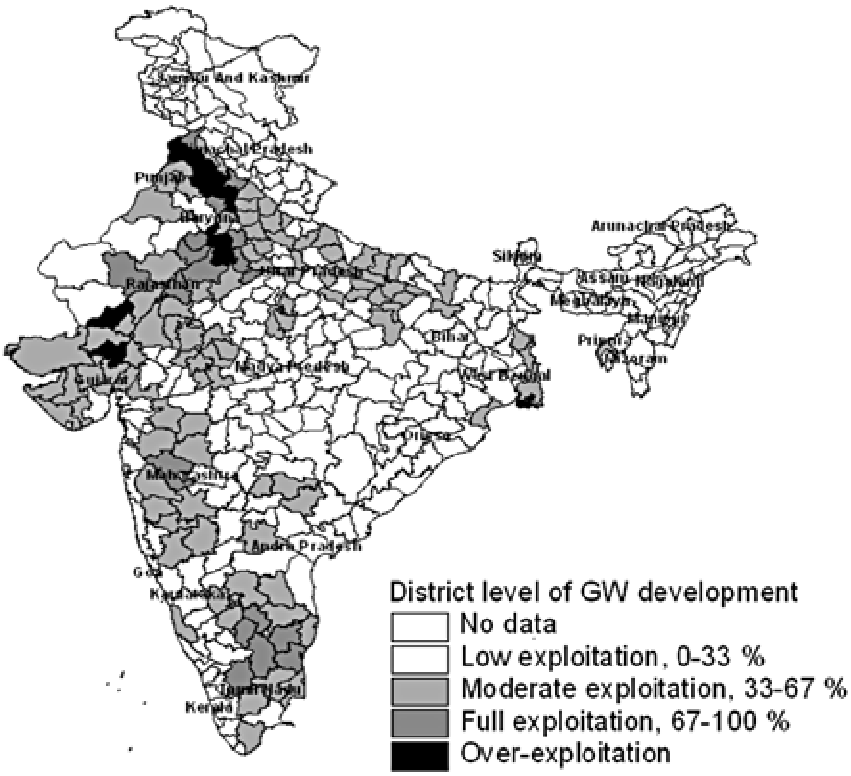


Figure 5. Level of groundwater development in India, district-wise (Data from Central Groundwater Board, 1995)

3. Make knowledge of groundwater and risk of over-abstraction easily understandable to the lay person and general groundwater user and other affected segments of society and establish communication links between users, scientists and managers.

Conclusions

Appropriate management options will depend on the specific hydrogeological context, the socioeconomic conditions and the level of groundwater development. Taking the outset in the Asian context, it needs to be realized that:

- Groundwater managers and researchers need a forum for exchange of experiences, views and approaches.
- This international workshop provides an opportunity to establish such forum.
- Groundwater management is about management of people and their impetus for exploiting the groundwater resource.
- Groundwater assessment and understanding of the physics and properties of aquifers is a prerequisite but not a means in itself. It should be incorporated into a wider process of data collection, information sharing and development of alternative management options.

- Mutual respect, appreciation, and understanding of roles, experiences and constraints and a common vision between groundwater managers and researchers are needed.

The Challenge Program on Water and Food[2] is funding a project on capacity building and multidisciplinary learning on groundwater governance in Asia[3]. This provides a further chance to build partnerships and networks across Asia to address general and specific, often shared, groundwater problems.

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[2]http://www.waterforfood.org/

[3]http://www.iwmi.cgiar.org/iwmi-tata/index.asp?nc=293&id=1002&msid=100

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