Strategic Analyses of the National River Linking Project (NRLP) of India
Series 1

India's Water Future: Scenarios and Issues

Upali A. Amarasinghe, Tushaar Shah and R. P. S. Malik, editors

International Water Management Institute

CGIAR Challenge Program on WATER & FOOD

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Preface

In 2005, the International Water Management Institute (IWMI) and the Challenge Program on Water and Food (CPWF) started a three-year research study on “Strategic Analysis of India’s River Linking Project”. The primary focus of the IWMI-CPWF project is to provide the public and the policy planners with a balanced analysis of the social benefits and costs of the National River Linking Project (NRLP).

The project consists of research in three phases. Phase I analyzed India’s water future scenarios to 2025/2050 and related issues. Phase II, analyses how effective a response NRLP is, for meeting India’s water future and its social costs and benefits. Phase III contributes to an alternative water sector perspective plan for India as a fallback strategy for NRLP. This book presents the findings of research in Phase I.

In 1999, the National Commission of Integrated Water Resources Development (NCIWRD) published projections of India’s water supply and demand to 2025/2050. The trends of key drivers before 1990’s were the basis for this projection. However, with economic liberalization, the trends of these key drivers changed in the 1990’s. Therefore, the major focus of research in phase I was to assess the trends and turning points of the key drivers in recent years and assess their implications on future water supply and demand.

This volume, the first in a series of publications, presents the results of various research activities conducted in Phase I on India’s Water Futures. Many papers in this book were presented in various regional and national workshops between 2006 and 2007. And, different versions are submitted for publication in various journals.

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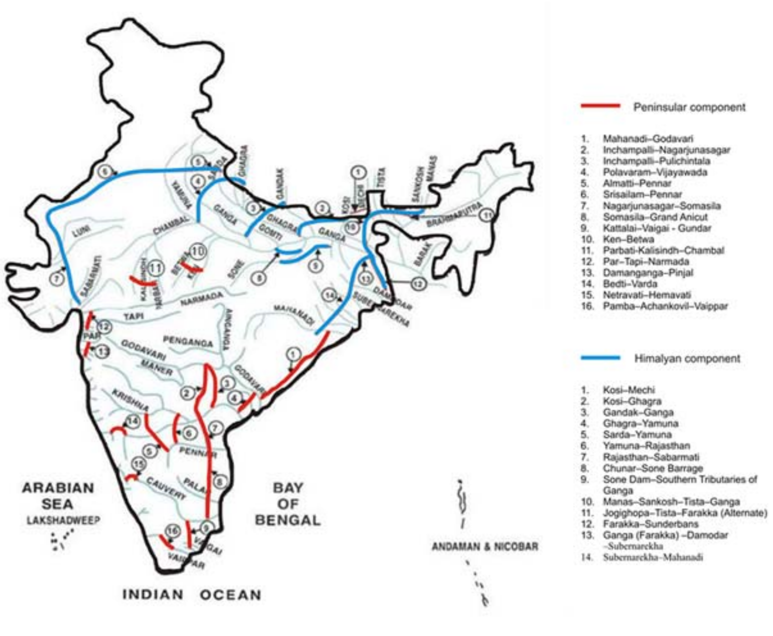
India’s National River Linking Project - A Synopsis

The National River Linking Project (NRLP) envisages transferring water from the surplus river basins to ease the water shortages in western and southern India while mitigating the impacts of recurrent floods in eastern India. NRLP constitutes two basic components — the links which will connect the Himalayan rivers and those which will connect the peninsular rivers (figure 1). When completed, the project would consist of 30 river links and 3,000 storage structures to transfer 174 km^3 of water through a canal network of about 14,900 km.

Figure 1. The Himalayan and peninsular components of NRLP project.



Components of the NRLP

The Himalayan component proposes to transfer 33 km^3 of water through 16 river links. It has two subcomponents linking:

1. Ganga and Brashmaputra basins to Mahanadi basin (links 11-14), and
2. Eastern Ganga tributaries and Chambal, Sabramati river basins (links 1-10).

The Peninsular component proposes to transfer 141 km^3 water through 14 river links. It has four subcomponents linking

1. Mahanadi and Godavari basins to Krishna, Cauvery and Vaigai rivers (links 1-9);
2. West-flowing rivers south of Tapi to north of Bombay (links 12 and 13);
3. Ken River to Betwa River and Parbati, Kalisindh rivers to Chambal rivers (links 10 and 11); and
4. some west flowing rivers to the eastern rivers (links 14 -16).

Project Benefits

The NRLP envisages to:

- provide additional irrigation to 35 million ha of crop area and water supply to domestic and industrial sectors;
- add 34 GW of hydro-power potential to the national grid;
- mitigate floods in eastern India; and
- facilitate various other economic activities such as internal navigation, fisheries, groundwater recharge, environmental flow of water-scarce rivers etc.

The NRLP, when completed, will increase India's utilizable water resources by 25 %, and reduce the inequality of water resource endowments in different regions. The increased capacity will address the long ignored issue of increasing India's per capita storage, which currently stands at a mere 200 m^3/person as against 5,960; 4,717 and 2,486 m^3/person for the US, Australia and China, respectively.

Project Costs

The NRLP will cost more than US$120 billon (in 2000 prices), of which

- the Himalayan component costs US$23 billion,
- the Peninsular component costs US$40 billion, and
- the hydro-power component costs US$58 billion.

Contentious Issues

The NRLP has many contentious issues to tackle, and these include the following:

- Resource mobilization, despite the fact that India finds it difficult to finance the completion of even the existing uncompleted projects;
- Environmental concerns, as it will
  - increase seismic hazards,
  - transfer river pollution,
  - destroy forest and biodiversity, and
  - change the ecological balance of land and oceans, and freshwater and sweater ecosystems;
- Social issues, as it will
  - displace more than 580,000 people under the peninsular component alone, and submerge large areas of agriculture and nonagricultural land;
- Cost recovery issues, as
  - the interest on the capital during the construction could be twice the estimated cost, and
  - the annual installment and interest on the capital could be more than Rs. 17,000/acre; and
- Political issues, which include issues regarding
  - Interstate water transfers, and
  - Water transfers between riparian countries-Nepal, Bangladesh and Buthan.

Part I

India’s Water Futures: Drivers of Change, Scenarios and Issues

Overview of the Research in Phase I of the IWMI-CPWF Project on ‘Strategic Analyses of India’s River Linking Project’

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Introduction

India is a vast country and its water availability varies significantly across regions and river basins. Water is in plenty in the north-eastern region, but few people live there and food production is low. In the north-western region most of the water resources are diverted for crop production, to such an extent that this region supplies food to the food deficit regions of the country, making it the largest provider of virtual water, that is, the water embedded in food. Water is scarce in the southern and western parts of the country, as the naturally drier areas come under increasing demand. Recurrent floods in the east and droughts in the south and west compound water related challenges that India is facing today. All indications are that India is heading towards a turbulent water future (World Bank 2005).

Proposed as an effective solution to the turbulent water future, the National River Linking Project (NRLP) envisages meeting India’s future water needs up to 2050. The NRLP plans transferring surplus waters of the Ganga, Brahmaputra, Meghna, Mahanadi and Godavari river basins to the water scarce basins in the southern and the western parts. But, the proposed project is a major contentious issue in public discourses in India and outside India. On the one hand, opponents argue that the concept of NRLP itself is dubious and the water need assessment of the project is not adequate. The environmentalist view is that the assessment of water surpluses in river basins has ignored many ecosystem water needs. Activists say NRLP will displace millions of poor, mainly tribal population. And, others argue that the alternative water management options are less costly, easily implementable and environmentally acceptable. On the other hand, the proponents vision NRLP as the best option for facing India’s turbulent water futures. They argue that NRLP will increase the potentially utilizable water resources and address the regional imbalances of water availability due to spatial variation of rainfall. However, many of the arguments, for and against the NRLP project so far, are based on assertions and opinions, and lack analytical rigor.

The International Water Management Institute and the Challenge Program for Water under the Consultative Group on International Agricultural Research (CGIAR) have started a three year research project for assessing India's Water Futures to 2025/2050 and analyzing what alternative options, including the River Linking Project, are adequate for meeting the future water challenges (CPWF 2005). The research project to some extent also attempts to fill the void of analytical rigor in the discourse on the NRLP to date. The specific objectives of the project are to:

- assess the most plausible scenarios and issues of water futures given the present trends of key drivers of water demand;
- analyze whether the NRLP as a concept can be an adequate, cost effective and a sustainable response in terms of the present socioeconomic, environmental and political trends, and if India decides to implement it, how best the negative social impacts can be mitigated; and
- contribute to a plan of institutional and policy interventions as a fallback strategy for NRLP and identify best strategies to implement them.

Phase I of the project focused on analyzing India's water future scenarios unto 2025/2050 and issues related therewith. This sets the stage for analyzing options for meeting water futures. Phase II, analyses how effective a response NRLP is for meeting India's water futures and its social costs and benefits. Phase III contributes to an alternative water sector perspective plan for India as a fallback strategy for NRLP. IWMI and CPWF would like to disseminate these findings of the research amongst the policy makers and the general public. The findings shall also add value to the on going debate on the NRLP, which is important to India and also to the neighboring countries of the region. This book is the first of a series of publications that brings out the results of the studies conducted under various themes of the project and also presented in various national workshops.

This volume, based on the studies conducted in the analysis in Phase I, has two parts. Part I, re-examining the key assumptions justifying the NRLP, provides an overview of the business as usual scenario and possible deviations of key drivers; gives a fresh look of the water supply and demand scenarios; and discusses some short to medium term policy options for meeting water needs of the immediate future. Part II presents the background studies conducted for the India's water futures analysis. These studies have assessed the recent trends, both spatial and temporal, of the key drivers of India's water futures. While some studies have projected the growth or estimated the requirements of key drivers in the future, others have assessed possible growth patterns and the constraints and opportunities of future growth.

India's Water Futures: Key Drivers of Water Supply and Demand

India is indeed a large country in many aspects that water has an intimate relationship. With more than one billion people, it has the world's second largest population now, behind China, and will have the world's largest population by the middle of this century. With more than a quarter of the population active in agriculture economic activities, it also has the world's second largest population whose livelihoods directly depend on agriculture. With agriculture supporting livelihoods of a large population, India also has the world's largest cropped area. With large crop areas under arid to semi-arid climatic conditions, it also has the world's largest irrigated area. With food gains as the staple food, India is the world's largest consumer and producer of cereals and pulses, and most of that, produced under irrigated conditions. With milk as the major animal product in the diet, Indian agriculture raises the world's largest cattle and buffalo population. And above all, it has the world's largest poor population and the majority of them live in rural areas and depend for their food security and livelihood on subsistence agriculture. And, India is also one of the large economies in the world with an impressive economic growth in recent years. Indeed, water has an important relationship to many of the above. And, water has shown to play an increasingly integral role in the rural livelihoods and economic growth.

Many drivers, either exogenous or endogenous to water system influence India's water futures (IWMI 2005). The exogenous drivers are mainly the primary drivers that set the direction of water futures. Some of the key drivers that are exogenous to water system of India are:

- changing demographic patterns;
- nutritional security and rural livelihood security;
- changing life style and consumption patterns;
- national food self-sufficiency;
- economic growth of India and that of other major regional economic powers;
- globalization and increasing world food trade;
- participation of private sector and nongovernmental organizations;
- political stability and relations between states and neighboring countries;
- technological advances, especially in water saving techniques; and
- global climate change.

The endogenous drivers to water system of a country are secondary drivers. They often are responses to the directions set by the primary drivers. Some of the key secondary drivers of the water futures of India are:

- changing agriculture demography;
- increasing water productivity;
- expanding groundwater irrigation and overexploitation;
- improving rain-fed agriculture;
- artificial groundwater recharge;
- rainwater harvesting;
- environmental water needs;
- recycling of urban waste water and marginal or poor quality water use;
- advancements in biotechnology; and
- desalinization etc.

Various assumptions on the direction and magnitude of these key drivers give rise to different scenarios of water futures. For example, nutritional security of all the people, livelihood security of rural population and food self-sufficiency of India were primary drivers of future water demand projections of the National Commission of Integrated Water Resources and Development (NCIWRD) (GOI 1999). Two population growth scenarios have given rise to the NCIWRD's low- and high-water demand projections (Verma et al. in this volume). The NCIWRD scenarios are considered to be the blueprint for future water development of India. And, the NRLP was virtually triggered by the projections of the NCIWRD high-water demand scenario. These scenarios were developed using the information on primary and secondary drivers available at the time of their projections. But the settings that surround these assumptions constantly change. A slight change of the assumptions of key primary drivers could significantly change the direction and magnitude of secondary drivers, and accordingly, the outcome, that is India's water futures (Paper 2 by Verma and Paper 3 by Amarasinghe et al. in this volume and Amarasinghe et al. 2007).

To what extent can the magnitude of these key drivers change in the future? The magnitude of the changes depends on vital turning points of primary drivers and the responses to them thereafter. Many turning points, which are usually difficult to predict, are mainly based on unforeseen human actions, political compulsions or natural catastrophes. Although turning points are difficult to predict, past trends of secondary drivers, which are largely the human responses to turning points, offer the best guide for us to extrapolate the likely course of trends to assess scenarios of water futures and explore policy options for meeting them. The assumptions of the primary and secondary drivers of the NCIWRD were mainly based on the priorities and trends in the 1980s. Before 1990s, livelihoods of a significant part India's rural population largely depended on agriculture. And, agriculture was the main engine of economic growth. With a large rural population and low foreign exchange reserves for large food imports, rural livelihood security and national food self-sufficiency were high priority then. However, the economic liberalization, which started in early 1990, has changed the course of many drivers. The various studies in this volume assess the turning points and recent trends of key drivers and their implications on India's food and water future scenarios.

Water Supply Drivers

Total Renewable Water Resources

The total renewable water resource (TRWR) of a country is the amount of resources that are available for utilization within its borders. The TRWR consists of water resources generated by endogenous precipitation within the borders—the internally renewable water resources (IRWR), and the net inflow from other countries through natural processes or allocated by treaties—the externally renewable water resources (ERWR). With 1,896 billion cubic meters (BCM) of surface runoff—636 and 1,260 BCM of ERWR[1] and IRWR—India has the seventh

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[1] ERWR is the net inflow to India. Inflows to India are from Nepal and Burma and outflows from India are to Pakistan and Bangladesh.

largest, and about 4 % of the total renewable water resources (TRWR) of the world (CWC 2004). However, due to un-even rainfall, TRWR vary significantly across river basins (Table 1). Basins in the north and east, Ganga, Brahmaputra and Meghna, Mahanadi and Godawari, have most of India's IRWR (Table 1).

Climate change, an exogenous driver to the water system, increases the spatial and temporal variation of TRWR. Recent studies show that with climate change, Mahanadi, Brahmani, Ganga and Godavari will experience higher precipitation and larger surface runoff, while many peninsular basins will experience lower rainfall and lower surface runoff (Gosain et al. 2006[2]). Although, the aggregate of TRWR at the national level show no major changes, regional disparities are likely to increase further. Moreover, with increasing incidence of high-intensity short-duration rainfall events due to climate change, the temporal variation of surface runoff will also increase (Mall et al. 2006).

Table 1. Water resources of India.

River basins	Total water resources (TRWR)	Utilizable surface water resources	Total ground-water resources	Potentially utilizable water resources (PUWR)	PUWR - % of TRWR
	km3	km3	km3	km3	%
Indus (Up to border)	73.3	46.0	27	72.5	99
Ganga	525.0	250.0	172	422	80
Brahmaputra and Meghna	585.6	24.0	36	60	10
Subernarekha	12.4	6.8	2	9	70
Brahmani-Baitarani	28.5	18.3	4	21	74
Mahanadi	66.9	50.0	17	66	99
Godavari	110.5	76.3	41	117	106
Krishna	78.1	58.0	26	84	108
Pennar	6.3	6.9	5	12	187
Cauvery	21.4	19.0	12	31	147
Tapi	14.9	14.5	8	23	153
Narmada	45.6	34.5	11	45	99
Mahi	11.0	3.1	4	7	64
Sabarmati	3.8	1.9	3	5	135
WFR1[1]	15.1	15.0	11	26	173
WFR2[2]	200.9	36.2	18	54	27
EFR1[3]	22.5	13.1	19	32	142
EFR2[4]	16.5	16.7	18	35	212

Source: GOI 1999, CWC 2004

Notes: 1- WF1 includes west flowing rivers of Kutch, Saurashtra including Luni; 2 – WF2 includes west flowing rivers between Tapi and Kanayakumari; 3. EF1 includes east flowing rivers between Mahanadi and Pennar; 4. – EF2 includes east flowing rivers between Pennar and Kanayakumari; 5 – Minor river basins drainage into Bangladesh and Myanmar

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[2] Brahmaputra and Indus were not included in this study.

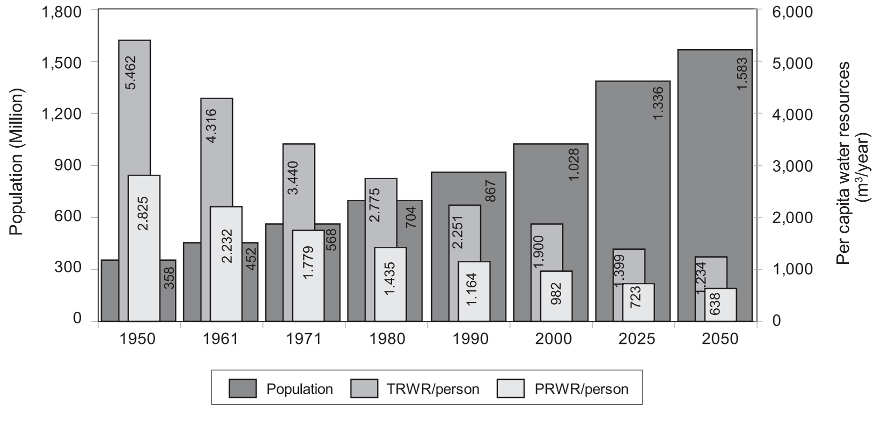
With monsoonal weather patterns, most of the rain that contributes to TRWR in many river basins falls in less than 100 days in the summer months between June and September and a major part of precipitation falls in locations where surface runoff cannot be captured due to limited storage potential. Therefore only a part of the TRWR can be stored or diverted for human use within a basin.

Potentially Utilizable Water Resources (PUWR)

The PUWR is the portion of the TRWR that can be captured for human use within a river basin. This depends on the variation of precipitation and the potential of storage and diversion facilities. For India, this is estimated to be only 58 % of the TRWR. Among the river basins, Brahmaputra and Meghna have the largest TRWR, but with limited storage opportunities, only 10 % of TRWR can be captured as PUWR (Table 1).

The population growth, an exogenous driver to the water system, exacerbates the limitations of PUWR in some locations. The PUWR per person in India in the middle of this century is projected to be 701 m^3, which is only 22 % of the PUWR per person in the middle of last century, indicating more than four-fold increase of population over this period (Figure 1). Few basins, which are already water stressed now (Amarasinghe et al. 2007), will have very low per capita PUWR by 2050. Such conditions—below 500 m^3 of per capita PUWR—are, as Falkenmark et al. 1989 described are extremely unhelpful even for human existence.

Figure 1. Growth of population and declining per capita water supply in India.



Climate change, an exogenous driver to the water system could also reduce PUWR. With increasing incidence of high intensity and short duration rainfall events, the incidence of flash floods increases. Thus, the capacity to capture or divert water will diminish and as a result PUWR will reduce. The PUWR will also be reduced in basins that are predicted to have low rainfall and runoff. Although the magnitude of the reduction in PUWR is still not exactly clear, the PUWR of many Indian river basins could reduce with climate change.

However, various responses are available for augmenting PUWR in water stress regions. Rainwater harvesting (RWH), artificial groundwater recharge (AGWR) and intra-basin or interbasin water transfers (IBWT) are three popular methods practised for augmenting PUWR. The RWH and AGWR are mainly local level interventions and they will generate immediate impacts in a neighborhood of the location where water is captured. On the other hand, the IBWT, which generally requires large infrastructure development, including storage reservoirs, barrages, river links, and distributary canals etc., can increase water availability in far away locations from where water is originally stored or diverted. However, these interventions could incur social cost too. Extensive RW and AGWR in the up-stream of river basins, especially in those which are approaching closure, can impact the uses and users in the down-stream of a basin. The IBWTs can displace many people and submerge large areas of forest or productive land. Yet, all these interventions can have significant spatially distributional benefits. The main question here however is, that with a significant part of the precipitation occurring in short spells, how much can these interventions effectively augment PUWR in Indian river basins?

Rainwater Harvesting

The extent that RWH can augment the PUWR depends on the capacity of RWH structures to store part of the unutilizable water resources. The exact estimates of this are sketchy. The study by Bharat et al. (Paper 10 in this volume) using a district level analysis shows that 99 km^3 of surface runoff are available for rainwater harvesting in 25 million ha of rain-fed lands. These lands exclude the extreme arid and extreme wet rain-fed areas. However, whether all of this quantity of harvested water will augment the net PUWR is not clear. Some harvested water could well have been captured by reservoirs in the downstream, and may already have been included in the present estimate of PUWR. In spite of whether it net augments or not, the RWH is very useful for distributing significant positive benefits to vast areas that a few storage structures cannot provide. Bharat et al. study also shows that it requires only about 20 km^3 of the above runoff to be captured to bring relief to about 25 million ha of rain-fed lands suffering from mid-seasonal droughts. If this portion can be part of the unutilizable water resources, then it is only 2.5 % of the unutilizable runoff and augments the present estimates of PUWR only by 1.7 %.

There are other viewpoints of RWH too. Kumar et al. 2006 argue that the impacts of many local watershed level RWH interventions will not always aggregate at the basin level. This argument is based on the premise that much of the water that RWH captures is part of the water already captured and used in the downstream. According to Kumar et al. the potential of RWH for net augmenting of PUWR in water scarce areas is low due to varying hydrological regimes, extremely variable rainfall events, and constraints of geology. Furthermore, the demand for water is low in locations where rainwater can sufficiently be captured, thus generating only a small economic benefit vis-à-vis to the cost of construction of many RWH structures.

Artificial Groundwater Recharge (AGWR)

The total renewable groundwater resource of India is estimated to be 432 BCM. For the country as a whole, only about 37 % of the renewable groundwater resource is withdrawn at present. But, with intensive withdrawals for irrigation, groundwater resources of some regions are severely over-stressed. The number of overexploited bocks is increasing, where groundwater abstraction well exceeds the replenishable recharge (CGWB 2008). Yet, the uses and users in the domestic, irrigation and industrial sectors that depend on groundwater are increasing. Sustaining the groundwater supply for various services, especially in the severely water stressed blocks and in areas approaching overexploitation, and maintaining the base flow in rivers in the dry season is indeed a major challenge.

AGWR have the capacity to alleviate the stress in groundwater overexploited areas. An ideal example is the mass movement of groundwater recharge in the Saurashtra region of western India (Shah 2000). According to the master plan prepared by the Central Groundwater Board, 36 BCM of unutilizable surface runoff can be captured through AGWR (CGWB 2008). This augments India's PUWR by 3.4 %. However, given the magnitude of the unutilizable surface runoff, many considered this estimate to be quite low. In fact, Shah 2008 argues that groundwater recharge using the existing dug-wells alone can exceed the potential of AGWR estimated in the master plan. Regardless of the magnitude of the recharge, AGWR is an important tool for net augmenting the PUWR and distributing the hydrological and economic benefits, as in RWH, to vast areas.

Intra-basin or Interbasin Water Transfers (IBWT)

The IBWTs perhaps have the potential for large net augmentation of PUWR. They can capture unutilizable runoff of water surplus basins through large reservoirs or barrages, and then transfer them to water scarce areas within the same or to other basins. For example, the NRLP envisages transferring 178 BCM from water surplus Brahmaputra, Maghanadi and Godavari basins to water scarce basins such as Krishna, Cauvery, Pennar, and Sabramati, in the southern and western regions (NWDA 2006). If all that diverted water in the NRLP is from unutilizable surface runoff, then it augments PUWR of India by 18 %. Indeed, this is one of the major contentious issues in recent discourses. How, such large quantum of surplus water, mainly floods, in some basins can be transferred to other basins when they also experience floods is indeed an important question.

In spite of the above concern, the IBWTs can have many socioeconomic and hydrological benefits. For example, the NRLP expects to mitigate the damage caused by floods which ravages the eastern parts of the country every year, temporarily displacing many people, destroying crops and livestock, and disrupting the livelihood of many, especially the rural poor. The NRLP also provides an insurance against recurrent droughts and expects to recharge groundwater of overexploited blocks in many parts of the southern and western parts of India. In fact, it can alleviate water scarcities in many river basins, which in some regions are becoming a serious constraint on further economic growth.

However, many other drivers, which are exogenous to the countries water system, also affect implementing IBWTs (Shah et al. 2006). Financing such mega projects, estimated to be more than US$125 billion (in 2000 prices) for NRLP, and their impacts on other social-welfare activities are serious concerns under the prevailing economic conditions at present. But, with rapid economic growth, increasing at 7-9 % annually in recent years, financing of large IBWTs shall not be a major constraint on a trillion dollar[3] economy in few years time.

The IBWTs often displace lakhs, if not millions of people and submerge large areas of forest and productive agriculture land. And the hardest hit by such displacements are the weakest sections of society, including tribal communities with forest as the main livelihood resource, and landless laborers who depend for their livelihood on the daily wages from working in those agriculture lands that get submerged. The resettlement and rehabilitation issues, if not properly addressed, are major bottlenecks for implementing large IBWTs.

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[3] India's GDP has already passed one trillion. It was US$1,027 billion in 2007.

Political stability and relations between states and neighboring countries are also major drivers of planning and implementing IBWTs. Often, IBWTs cut across several states and at times, several countries. In NRLP, it is even required to build storage reservoirs in other countries. Therefore, the existing level and the future prospects of trans-boundary or inter-state cooperation are major determining factors determining the feasibility of such IBWTs.

Ecosystem water needs, another major driver, is often ignored in IBWT planning. But they are highly contentious issues in the discourses thereafter. An important question often raised in these dialogues are whether water resources required for sustaining a healthy ecosystem in one basin can be considered for augmenting water resources in other basins. According to Bandyopadhyaya and Praveen 2003, there is no free surplus of water available to be transferred from one river basin to another basin. All water in the unutilizable water resources, including floods, performs an important ecosystem service. Such assumptions, indeed, are an extreme view point in-terms of ecosystem water needs. A compromised formula can determine the extent of surplus that can be transferred from the water surplus river basins. How much of water can be transferred depends on whether the environment is considered as a primary driver of water supply or as another sector of water use.

If environment is considered as another sector of water use, it often loses. With increasing demand, different sectors compete for scarce water resources. The agriculture, domestic, industrial, navigation and hydropower sectors have stakeholders who have a voice and also theoretically can afford to pay for the services. However, the environmental sector has no voice by itself or cannot pay for its water demand. Thus, as a ‘water use sector’, the water needs of the ecosystems are often ignored in IBWT planning. For instance, the NCIWRD water demand scenarios considered the environment as a water use sector, and allocated only 10 BCM, or less than 1 % of TRWR.

However, this situation can change if eco-system water needs are considered as a primary driver of water availability. The premise here is that parts of the floods in the rainy season and a minimum river flow in the dry season play a major role in servicing the needs of the riverine ecosystems. Thus, a major part of the unutilizable water resources cannot be captured and transferred for water use in other basins. In this context, it is important then to know the magnitude of the water needs for sustaining ecosystem services in river basins.

Environmental Water Demand

As a primary driver, a good starting point is to assume that at least a minimum environmental flow (EF)[4] requirement is to be maintained for providing ecosystem services of a river basin. Two factors determine EF. They are the natural hydrological variability of the river flow, an endogenous driver to the water system, and the environmental management class that the river ought to be maintained, often an exogenous driver to the water system. The latter depends on human decisions on the qualitative importance they want to place on riverine ecosystems. Smakhtin et al. (Papers 20 and 21) defined six environmental management classes (EMC), and

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[4] This is part of the research conducted under the project for assessing environmental water demand of river basins of India. Details of the procedures and estimation are available in Smakhtin and Anputhas 2007 (or paper 14 in this volume) and Smakhtin et al. 2007 (paper 15 in this volume).

determined the minimum flow if a river ought to be maintained under different EMCs. The EMC class A corresponds to the pristine conditions of a river. Other—classes - B to F - correspond to slightly, moderately, largely, seriously and critically modified river conditions. The EMCs E to F describe the development states of a river basin where the basic ecosystem functions are destroyed to the extent that the changes to the river ecosystem are irreversible. Table 2 shows the EF under different EMCs for 12 river basins of India, which account for 78 % of TRWR of India. The total EF of 12 basins varies from 70 % of TRWR in class A to 13 % in class F.

Table 2. Minimum river flows of Indian river basins.

River basin	Natural MAR[a]	Environmental flow (EF) – % of MAR					
	(Bm^3)	A	B	C	D	E	F
Brahmaputra	629.1	78	60	46	35	27	21
Cauvery	21.4	62	36	20	11	6	3
Ganga	525.0	68	44	29	20	15	12
Godavari	110.5	59	32	16	7	4	2
Krishna	78.1	63	36	18	8	4	2
Mahanadi	66.9	61	35	19	10	6	4
Mahi	11.0	42	17	7	2	1	0
Narmada	45.6	56	29	14	7	4	3
Pennar	6.3	53	28	14	7	4	2
Sabarmati	3.8	50	24	12	7	3	2
Subernarekha	12.4	55	30	15	7	3	2
Tapi	14.9	53	30	17	9	5	3
Total MRF demand (Bm^3)		1,065	731	501	353	260	202
Total - % TRWR		70	48	33	23	17	13

Source: Amarasinghe et al. 2007a

Note : [a] Mean annual river runoff

Ideally, one would like to maintain rivers in their pristine condition, or in EMC class A. The EF requirement for maintaining Indian rivers in EMC class A is even more than the estimate of the total unutilizable water resources at present. And, under such conditions, no water surpluses are available for transferring between basins, and it is feasible only in low populated and low developed river basins. Given the present level of population and economic growth, maintaining large EF as in EMC class A is impossible. In fact, none of the major rivers can be maintained in pristine conditions.

The total water requirement for maintaining rivers in EMC class B is 731 Bm^3. Although this level of demand is within the total unutilizable water resources of all river basins, a few rivers still require a substantial part of the utilizable water resources for meeting environmental water needs. The EMC class C maintains a river under moderately modified conditions. The minimum flow requirement under this scenario of all river basins, except Cauvery, Pennar and

Tapi, is less than the unutilizable water resources (Amarasinghe et al. 2007). The unutilizable water resources of Brahmaputra, Ganga, Mahanadi, and Godavari substantially exceed the corresponding EF under EMC class C. Thus part of the excess flows in these basins can theoretically be transferred to other basins. Nevertheless, if environmental water demand gets high priority, the effective water supply that is available for augmenting PUWR could further diminish in many river basins.

Besides these concerns, some studies show that the estimates of PUWR that are available at present are significantly over-estimated (Garg and Hassan 2007). This is mainly due to double counting of surface and groundwater resources in the dry season. According to Garg and Hassan, the presently available estimate of PUWR in India is overestimated by at least 66 %. Such estimates, indeed, are alarming and require thorough scrutiny before they are accepted in water supply and demand modeling and such a scrutiny also requires a clear understanding of the interaction of surface and groundwater flows in river basins, for which the available data on water resources in many river basins are inadequate. According to Mohile et al. (Paper 19 in this volume), a static estimate for PUWR is not any more a useful concept. Instead, they prefer to replace PUWR by 'limits of utilization' of water resources in a basin. The limits of utilization depend not only on the natural flows and the engineering and agronomic constraints, but also - on environmental constraints and methods of utilization of water resources. They propose that any surplus water over and above the 'limits of utilization' can be transferred to other basins. A major drawback of this approach is the way it estimates potential utilization in a river basin. It depends on a set of assumption of trends and magnitude of drivers of water demand and the potential water use according to them. As discussed before, these assumptions, especially on primary drivers, are difficult to forecast. Therefore, drivers pertaining to water demand estimation themselves require periodic assessment.

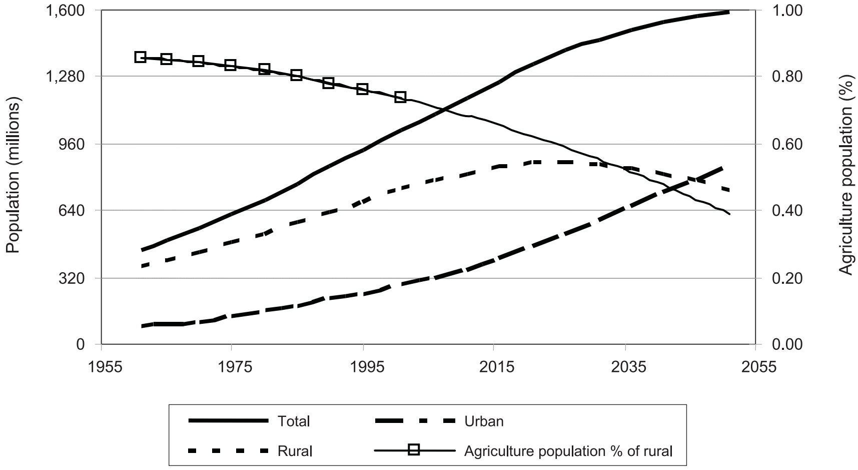
Water Demand Drivers

Changing Demographic Patterns

Population growth has a central place among primary drivers of future water demand. The changing regional demographic patterns also play an equally important role in assessing the composition of regional water demand. This is important for a large country like India with a significant spatial variation of water availability, and also when irrigation is the largest consumptive water use sector in many regions. Irrigation has played a vital role in the past in many states where a major part of the rural population depended on agriculture for their livelihoods.

But, the regional demographic patterns are changing with rapid urbanization. Study by Mahmood and Kundu (Paper 6 in this volume) projects India's total population to reach about 1.6 billion by 2050 and stabilize thereafter (Figure 2). It has been estimated that about 53 % of the population will live in urban areas by 2050. According to others, this is even a conservative estimate of urban population growth in India (Y.K. Alagh cited by Amarasinghe and Sharma 2008). In either scenario, demographic trends of many states will change significantly by the second quarter of this century. Many states will have more cities with major urban centers, and more urban than rural population.

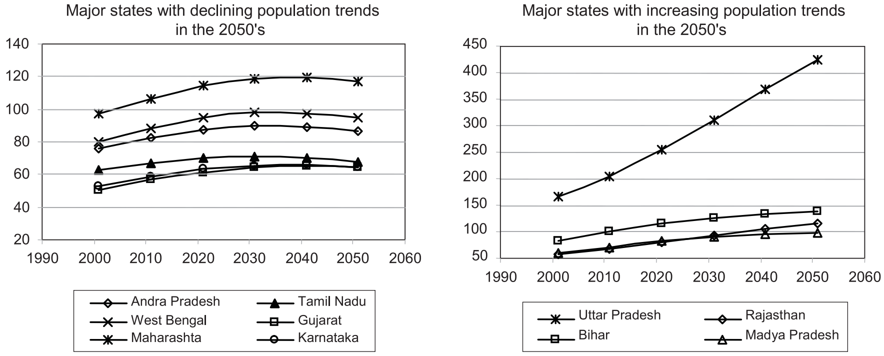
Figure 2. Urban, rural and agriculture depended population in India.



Source: FAO 2005, Mahmood and Kundu 2006

An examination of the demographic trends at the state level suggests that population of Andhra Pradesh, Kerala, Karnataka, Punjab and Tamil Nadu, will have a declining trend by 2050, and a significant part of the population of these states will live in urban areas (Figure 3). The states Haryana, Gujarat, Orissa, Maharashtra and the West Bengal will have moderately declining population. In all of the above states, water demand for the domestic and industrial sectors is likely to increase rapidly, and the water use patterns in the agriculture sector will change.

Figure 3. Population growth trends in major states.



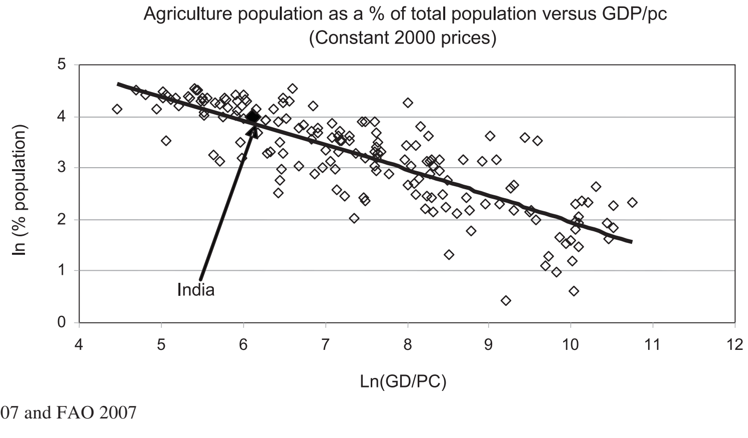
However, the so called 'BIMARU' states, Bihar (including Jharkhand), Madhya Pradesh (including Chhattisgarh), Rajasthan and Uttar Pradesh (including Uttaranchal) will only continue to have increasing population, but will continue to have a substantial rural population by 2050. The pressure for agriculture land and water will intensify in these states, where the natural resource base is already over stressed due to extensive agriculture activities.

Many national level projections often do not incorporate regional population growth patterns. This is one major shortcoming of the assumptions of the NCIWRD scenarios. They estimated the future population of states and basins on the basis of the 1991 population figures (page 70 in GOI 1999). Such an assumption can over estimate the rural population and part of the rural population that depend for their livelihood on agriculture in many southern and western states.

Rural Livelihood Security

Rural livelihood security, for which agriculture is the main source for many people, was a vital component of the overall rationale for agriculture water demand projections in the past. However, recent trends suggest that the agriculture demography is fast changing with increasing employment in the nonagricultural sectors. The study by Sharma and Bhaduri (Paper 7) suggests that India may be at the 'tipping point' of the transition in its agriculture dependent population to nonfarm activities. Agriculture will be a part-time employment activity for many habitants in rural areas. Over the last four decades, the agriculture-dependent population has declined from 86 to 74 %. This percentage is likely to decrease further, and could reach even below 40 % by 2050 (Figure 2). Such trends are compatible with the present level of agriculture population of countries with similar economic conditions that India shall experience by 2050 (Figure 4), and perhaps could accelerate in the future as the National Sample Survey show that significant number (40 %) of farmers say that would like to exit farming for better opportunities in the nonfarm sector.

Figure 4. Agriculture population across selected countries in the world.



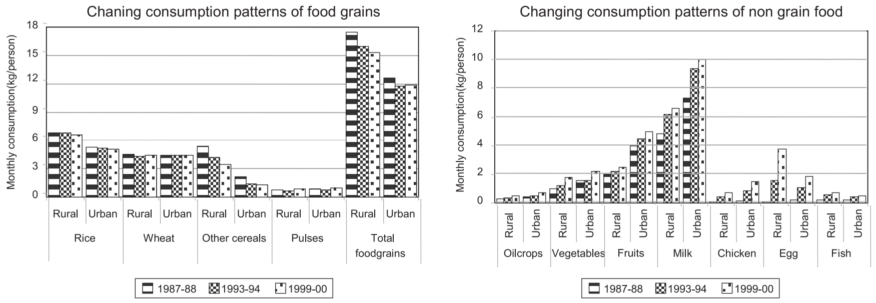
Source: WRI 2007 and FAO 2007

The implication of the changing agriculture demography is that, although the agriculture dependent population in India will increase in the near-term, the growth rate shall start to decline soon. And in 50 years from now, India will have even less population that depends on agriculture than it is now. Sharma and Bhaduri study further shows that withdrawal of rural youth from agriculture is not significantly related to access to irrigation. Rural livelihood security shall decline in importance as a primary driver in determining future irrigation water demand in India. This was another contentious assumption in the NCIWRD projections, where it was assumed that irrigated agriculture would be a major part of the future rural livelihood security.

Changing Consumption Patterns

Generally, the food consumption patterns of a country largely determine what its people produce in the agriculture fields. More than two-thirds of the food consumed in India at present is produced under irrigated conditions. And due to large marginal to small land holders, the producers are also the main consumers of the crops they produce. Thus, the local consumption patterns play a pivotal role in cropping pattern decisions in irrigated agriculture. In the past, grain crops dominated the agriculture production patterns, as food grains provided a major part of the daily nutritional intake. However, a subtle change in food consumption patterns has been surfacing in the recent past in both rural and urban India. While, the demand for food grains, especially for rice and coarse grains in both rural and urban areas are declining in the 1990s, the demand for non-grain food crops such as vegetables, fruits and oil crops, and animal products such as milk, chicken, eggs and fish is increasing (Figure 5).

Figure 5. Changing consumption patterns in rural and urban areas.



Source: NSSO surveys

Increasing income and urbanization will further increase the demand for non-grain food products in the Indian diet. The study by Amarasinghe et al. (Paper 8) in fact shows that non-grain crops (oil crops and vegetable oils, roots and tubers, fruits, vegetables and sugar), and animal products (mainly milk, chicken, eggs) are expected to provide a major part of the nutritional intake by 2050. Food grains provide more than two-thirds of the nutritional supply today, and this will reduce to less than half by 2050. As a result of decreasing per capita grain consumption in both the urban and rural areas, and the rate of urbanization, the total food grain demand will increase slowly. However, due to increasing consumption of animal products, the feed grain demand will increase several fold. The demand for non-grain crops will also increase substantially. Therefore, non-food grain crops will consist of a major part of the additional irrigation geography in the future.

This is quite in contrast to the assumptions of the NCIWRD scenarios, in which they projected a significantly high additional food grain demand. In fact, the NCIWRD projection of demand for food grains exceeds 22 kg/month/person by 2050, and that level of food grain consumption alone can provide a calorie supply of 4,000 kcal/person/day. Such level of calorie supply is highly unlikely as it is even higher than the calorie intake in the most developed countries with animal product dominated diet (Amarasinghe et al. Paper 3). Nevertheless, high demand for food grains along with national self-sufficiency assumption required NCIWRD scenarios to project a large irrigated area expansion.

National Self-sufficiency

Another primary driver that dominated the selection of cropping patterns of agriculture in general, and irrigation in particular was full national self-sufficiency of food grains. This assumption was mainly based on the three concerns that 1) India has a large population and the food grains are the staple food of its people with mainly a vegetarian diet, because of which large production deficits, such as in the 1960s, are not acceptable; 2) agriculture was the main driver of economic growth and has contributed to substantial part of the gross domestic product; and 3) India's foreign exchange reserves are too low to import large quantities of food from the world market. The first is still true, but as mentioned before, demographic and consumption patterns are fast changing, and demand for non-grain food and feed products are increasing. With changing consumption patterns, there will be more opportunities for Indian farmers to increase income from growing high-value non-grain food products. Moreover, India's agriculture export and import patterns are also changing. Although the share of total agriculture exports is decreasing, which is natural with rapidly growing industrial and service sectors, the total quantum of exports has been increasing in recent years (Paper 9 by R.P.S. Malik). Also, India has been importing a significant part of the requirements of vegetable oil, and also some pulses, fruits and nuts etc. However, the value of agriculture exports at present far exceeds that of imports, and the difference is widening gradually. And with expanding global trade, India will have more opportunities for increasing agriculture exports, and pay for its agriculture imports.

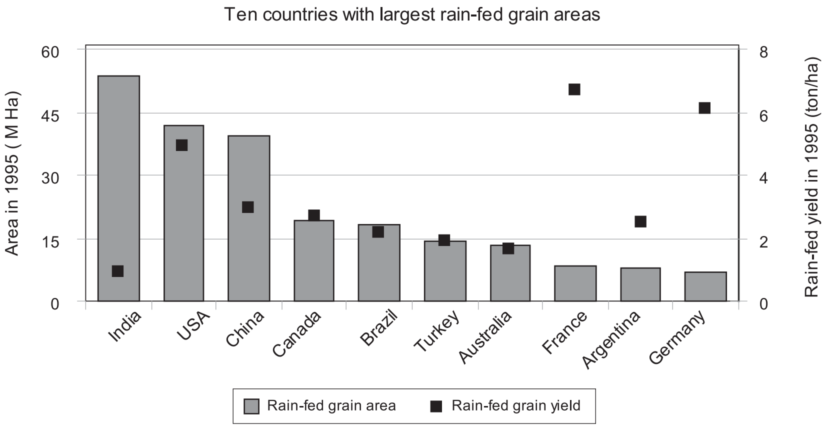
In the past, low foreign exchange reserves were indeed a constraint on large food imports. But that was only when the gross domestic product was only a few hundred billion dollars, and food grain production was a substantial part of it. But it is no longer valid under the prevailing economic growth. India has a trillion dollar economy now and has large foreign exchange reserves in comparison with those in the early 1990s. The share of the agriculture sector, let alone the value of food grain production, is only about 23 % of the total GDP in 2000 (WRI 2007). And this share will decrease further, and India will have sufficient foreign exchange reserves to pay for even large food imports in a few decades time.

However, the only concern that India should have in large quantity of food imports is its effect on prices. Potential price increases due to large food imports from countries such as India and China can hurt the very consumers that the imports would expect to help, and also can increase the volatility of global grain markets in the years of significant grain production deficits. So, a reasonable degree of food self-sufficiency, purely because of the volatility in the grain prices in the markets, can still be a good assumption for projecting future food and water demand.

Realizing the Potential in Rain-fed Agriculture

While India ranks the highest among the countries with rain-fed agriculture area, it ranks one of the lowest in rain-fed yield (Figure 6). The total food grain production from the existing land can be increased 30 % by raising the rain-fed yield by just one ton, which is still much lower than the rain-fed yields of many other large rain-fed food grain producers.

Figure 6. Rain-fed yield of major food grain producers in the world.



Source: IWMI 2000

Sharma et al. (Paper 10) finds that frequent occurrence of mid-season and terminal droughts were the main cause for crop failures or low yield in a major part of the rain-fed cropped area. Small supplemental irrigation during the water stressed periods of mid-season and terminal droughts can significantly increase the rain-fed yields. Providing supplemental irrigation through decentralized, more equitable and targeted rainwater harvesting structures can help millions of resource poor farmers in rain-fed faming. They shall also reduce the requirement for large-scale irrigation projects, which in the present states of water scarcities require large inter or intra-basin water transfers. However, small RWH interventions could bring maximum benefits provided that the marginal cost does not exceed the marginal economic benefits in basins with high degree of development and that there are no significant disparities of water demand in the upper and lower catchments, where there is no significant tradeoff in maximizing benefits of the upstream vis-à-vis optimizing the basin wide benefits (Kumar et al. 2006).

Increasing Crop Productivity

Assumption of the growth in crop yields is a major driver in determining the requirement of additional agriculture area and irrigation. For example, India can be self- sufficient in food grains without any additional irrigation if it doubles the crop yield in 50 years (Figure 7)[5]. If India can attain such level of productivity in 50 years from now, it is only similar to the productivity levels of China today, although both countries had more or less similar productivity levels 50 years ago. Indeed, there does seem to be a significant scope for increasing crop productivity over the next few decades.

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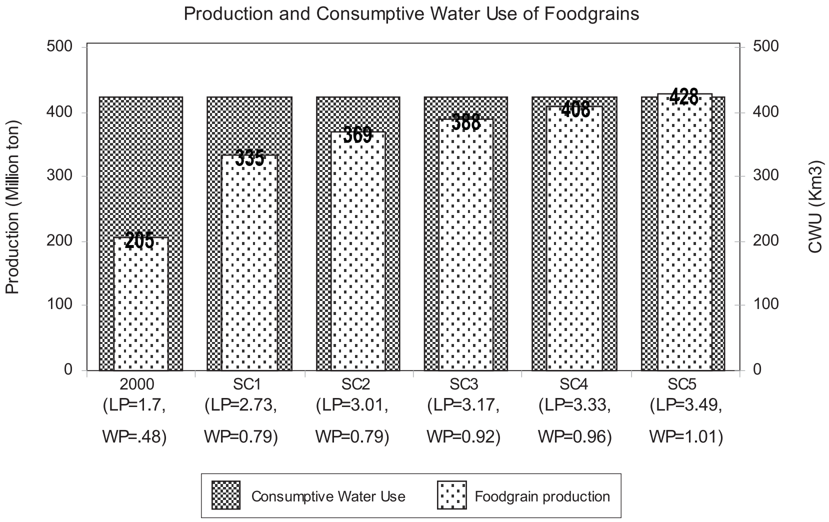
[5] In 2000, India was self-sufficient in food grains with a production of about 205 Mmt. The land and water productivity of food grains in 2000 was 1.67 ton/ha and 0.48 kg/m^3. With two-fold increase in land and water productivity, as shown in Scenario 4, India can increase food grain production over 400 Mt without any additional consumptive water use. This level of production is more than sufficient to meet the consumption demand of 377 Mmt projected by Amarasinghe et al.; Paper 6).

Figure 7. Food grain production under different land and water productivity scenarios.



Source: Authors estimate using PODIUMSIM

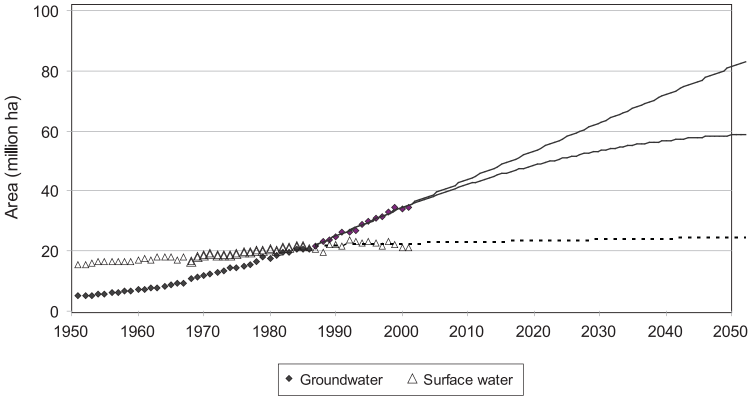
Kumar et al. (Paper 14) show that significant variations of productivity exist across farms in the same area and irrigation systems in the same regions growing similar crops. They conclude that a significant scope exists for increasing crop productivity in irrigated areas by manipulating key factors which include reliable irrigation supply and input use. As shown by Sharma et al. (Paper 10), small supplemental irrigation can double the productivity of crops in rain-fed areas. Study by Palanisami (Paper 13) explores ways of increasing the value of productivity through multiple cropping systems. This is a good strategy when there are limited opportunities for increasing productivity through mono-cropping systems.

Growth in Irrigated Area

Over the last few decades, irrigation expansion was the sole contributor to the growth in gross cropped area, and groundwater was the main driver behind this area expansion. In fact, the groundwater irrigation has contributed to all of the net irrigated area expansion in the 1980s and 1990s (Figure 8). Today it accounts for 60 % of the gross irrigated area of India. It shows that much of the expansion in recent decades, contrary to popular belief, has occurred outside major canal command area districts (Bhaduri et al.; Paper 11). In fact, the groundwater irrigation explosion in the last few decades was driven mainly by the population pressure and not necessarily by the water availability through return flows of surface water irrigation. Although the depth to groundwater in some areas is falling, overall expansion for groundwater shall continue in the future in many other regions.

The groundwater irrigated area has expanded at a rate of one million ha annually during the last decade and, in comparison, the surface irrigated area had virtually no growth over the same period. The NCIWRD scenarios assumed that much of the expansion in irrigated areas that will be required for meeting future food demand will come from surface irrigation. However, the trends in the 1990s show a stark deviation from this assumption. Such assumptions indeed

Figure 8. Net surface and groundwater irrigated area growth.



Source: GOI 2004; Amarasinghe et al. 2007.

have major implications on the financial cost and also on the total water demand. As regards the cost, expanding surface irrigation under the prevailing water scarcity conditions in many river basins will most probably require expensive IBWTs. As regards the water demand, surface irrigation may require significantly higher water withdrawals, as project efficiency of surface irrigation is much lower than groundwater irrigation.

Based on the present level of exploitation, availability, quality and the impact on environment, Sundararajan et al. (Paper 12) argue that there are only small pockets for developing further groundwater irrigation. However, as argued by Amarasinghe et al. (Paper 4), artificial groundwater recharge is an important policy prescription for sustaining the groundwater irrigation in many river basins. And, based on the present trends, Amarasinghe et al. 2007 shows that groundwater expansion will continue and the net groundwater irrigated area will reach about 50 mha, adding further 16 mha to the level in 2000.

Increasing Efficiency

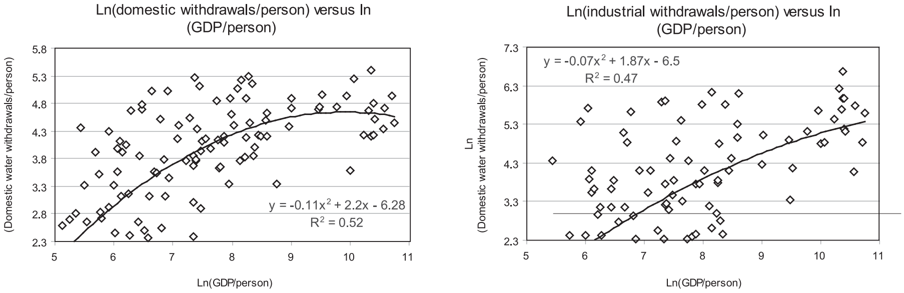
The project efficiencies of surface and groundwater irrigation systems are another major driver affecting irrigation demand projections. Many claimed that there is a significant scope for increasing project efficiency, especially in surface irrigation systems. However, the little information available suggests that the efficiencies of major systems are hovering around 30-40 % and no major increment of efficiency was also seen over the last few decades. Indeed, increasing irrigation efficiency in one location of river basins that are approaching closure may not yield the desired result of gains in overall efficiency, as it affects another user in the downstream of the closing basins. Thus, increasing surface irrigation efficiency to the level suggested by the NCIWRD projections, i.e., 60 % will have limited effect within the water stressed basins.

But it is clear that many water saving technologies, especially micro-irrigation systems, can significantly increase water use-efficiency. Narayanamoorthy (Paper 15) show that sprinkler and drip irrigation can have efficiencies in the range of 75-90 %. And, it also shows that more than 70 mha of land can potentially benefit from micro-irrigation. However, this potential can only be reached by overcoming many constraints. Spreading micro-irrigation systems in India is difficult due to the many marginal and small farmers, lack of independent source of water and pressurizing devices for these small farmers, poor extension services, lack of subsidies, unreliable electricity supplies etc. (Kumar et al. Paper 16).

Domestic and Industrial Water Needs

The economic growth, increasing income and lifestyle changes drive up the demand for water for the domestic and industrial purpose. Figure 9 shows that water demand in the domestic and industrial sectors increase rapidly with increasing income in the low to middle-income categories and the growth of water demand, especially in the domestic sector tends to stabilizes at the higher income level.

Figure 9. Domestic and industrial water demand in different countries.

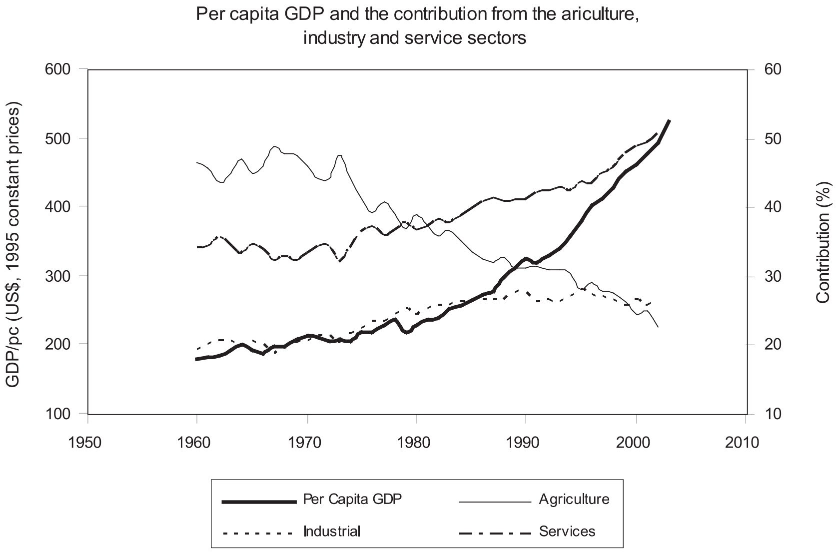


Source: WRI 2005

In India, the service and industrial sectors expanded rapidly in the 1990s and contributed to a GDP growth of more than 5.1 % annually between 1991 and 2002 (Figure 10). Over this period, per capita GDP has increased at 3.9 % annually, and it is growing 5.3 % annually in this decade. Such growth patterns in the economy will exert a significant pressure for water demand in the domestic and industrial sectors in the future. In fact, according to the current trends of economic growth and urbanization, most of the additional water demand between 2000 and 2050 could well come from the domestic and industrial sectors (Amarasinghe et al.; Paper 5). Whether that increasing water demand will be met through groundwater or surface water is an important secondary driver for assessing future water needs.

A national-level analysis (Sundararajan; Paper 19) reveals a significant spatial variation of the dependence of groundwater for municipal water supply. In peninsular India, primarily in hard rock regions, cities depend more on (average around 80 %) external sources of water. The size of a city is a strong indicator of how much surface water it can import from other areas. The alluvial aquifer cities are more dependent on local groundwater (average 75 %). However, as the city population grows its dependence on surface water will increase. And their willingness to pay for a reliable service shall increase too. Thus, growing cities and their population in India will be a major driver of increase in surface water for domestic and industrial sectors in the future. Such increase in demand could be a major justification for large intra-basin water transfers.

Figure 10. Contribution to GDP growth from different sectors in India.



Source: WRI 2006

Conclusion

There are clear trends that India will require substantial additional water supply to cater to increasing demand in the coming decades. It is estimated that India withdrew about 680 BCB for meeting the demand in the irrigation, domestic and industrial sectors in 2000. According to the recent growth patterns, the future demand is projected to increase by 22 % and 32 % by 2025 and 2050, respectively (Amarasinghe et al.; Paper 4). The population and economic growth, increasing world trade, the changes in lifestyles and food consumption patterns, technological advances in water saving technologies are the most influential primary drivers of India's water future in the short to medium term. The climate change will become an influencing factor in the long-term.

Over the last two decades, groundwater has been the major source for meeting increasing demand in all sectors. It is highly likely that this trend will continue. However, many river basins will have severe water stress conditions under business as usual water- supply and use patterns. With increasing reliance on groundwater, particularly for irrigation, many river basins will have severe groundwater overexploitation-related problems. Indeed, meeting India's short to medium term water demand itself will be a challenging task.

However, many options are available to meet this challenge (Amarasinghe et al.; Paper 5). Recharging groundwater to increase the groundwater stocks; harvesting rainwater for providing the life-saving supplemental irrigation; promoting water saving technologies for increasing water use efficiency; formal or informal water markets and providing reliable rural electricity supply for reducing uncontrolled groundwater pumping; increasing research and extension for enhancing agriculture water productivity; and carefully crafted virtual water trade between basins are important policy options for meeting the increasing demand. With increasing disposable income, people's affordability and willingness to pay for a reliable domestic and industrial water supply will increase. This, along with a reliable water supply for diversifying high value cropping patterns, may require large surface water transfers. The interbasin water transfers could increase the recharge groundwater in much overexploited area.

While artificial groundwater recharge, rainwater harvesting, and interbasin water transfers are a solution for meeting the water demand in the near-term, they are also solutions for increasing the potential utilizable water supply in many water scarce river basins. They will indeed have major benefits when full influence of the climate change starts to impact the utilizable supply in many water scarce river basins.

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India’s Water Future 2050: Potential Deviations from ‘Business-as-Usual’[1]

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Background

India has for long been toying with the idea of having a national water grid to overcome the spatial inconsistencies in demand and availability of fresh water resources. The idea of transferring the flood waters of the Ganga-Brahamaputra-Meghna (GBM) basin to the water-starved basins in western and peninsular India has been in existence for long[2]. More recently, the idea acquired a new life when, based on a public interest petition, the Supreme Court of India issued an order directing the government to implement the plan prepared by the NWDA[3] in 10 years. The government, in response to the court directive, set up a (now disbanded) high-powered task-force with the mandate to complete an analysis of how the project will unfold by December 31, 2006 and subsequently to complete, by 2016, the project in this respect that will cost roughly US$120 billion and link 37 Himalayan and peninsular rivers. The project (National River Linking Project – NRLP) “will form a gigantic South Asian water grid which will handle 178 km^3 of inter-basin water transfer/year, build 12,500 kms of canals, generate 35 gigawatts of hydropower and add 35 mha to India’s irrigated areas” (IWMI 2003).

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[1] This paper is a modified and updated version of a paper by the same authors and with the same title published in the ‘International Journal of Rural Management’, Sage Publications (Verma and Phansalkar 2007).

[2] It started in late nineteenth century when Sir Arthur Cotton thought of a plan to link rivers in southern India for inland navigation. The idea was partially implemented but was abandoned with time as inland navigation lost ground to railways. In 1972, the then Union Minister for Irrigation, Dr. K.L. Rao, proposed the Ganga-Cauvery link and again, in 1977, Captain Dinshaw Dastur coined the phrase ‘Garland Canal’ and while his plan was later rejected, the catchy phrase caught the imagination of people and continues to be popular.

[3] The National Water Development Agency (NWDA) was set-up by the Government of India (GOI) in 1982 to work out basin-wise surpluses and deficits and to study the possibilities of storage, links and transfers. It proposed two components of a mega river-linking plan – Himalayan and Peninsular – envisaging 14 and 16 links, respectively.

The 'task force' repeatedly cited projections made by the National Commission for Integrated Water Resource Development (NCIWRD 1999) of the increased irrigated area required to feed the growing population as the key justification for NRLP. In this paper, we try to identify grey areas and points of discontinuity with the aim of evolving a research agenda that will lead to a refined, textured and nuanced understanding of India's water future 2050. The paper is organized as follows. First, we present an overview of India's water resources; second, we provide a summary of the projections made by the NCIWRD; third, we review other projections for water availability and demand made at global and regional scale with special reference to India; fourth, we discuss potential deviations from the commission's projections; and, finally, we conclude with a framework for 'water future' research.

Setting the Stage: India's Water Resources

How much water do we have? How much of it is currently being used? How far can it be stretched further? Ironically, even the best estimates on these basic questions are often confusing, inaccurate or inconsistent. In this section, we address these questions in a simple and coherent manner to provide the reader a backdrop for NCIWRD's estimates[4].

Water Resource Accounting

India has a geographical area of a little over 329 million hectares (MHa), and a mean annual rainfall of 1,170 mm. This mean annual rainfall is added to the snow-melt in glaciers and net cross-border river-inflow (river-flow originating from outside India and coming into India MINUS river-flow originating in India and draining to a neighboring country) to calculate average annual precipitation. This amounts to around 4,000 BCM[5]. Of this, less than half is 'accounted-for' while the rest constitutes what may be called the 'unaccounted' water resources of India. This 'unaccounted' water is primarily used-up in four processes:

(1) Evaporation: A major portion of this 'unaccounted' water is lost to the atmosphere in the form of evaporation. As the rain falls, a good amount of it is first intercepted by the foliage and this amount returns to the atmosphere without ever reaching the ground. This 'deduction-at-source' takes place in every spell of rainfall. However, this rain does get measured by the rain gauges which are always kept in open areas, and is thus included in the above 4,000 BCM. Besides the evaporation of rainwater, the evaporation taking place from land area and water bodies accounts for a large amount of the 'loss'.

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[4] All figures quoted in this section are with reference to the NCIWRD 1999 report, unless otherwise stated. The authors would like to acknowledge the help of Mr. Chetan Pandit, Mr. A.D. Mohile, Dr. Christopher Scott and Dr. M. Dinesh Kumar for their inputs and useful comments on previous versions of this paper.

[5] BCM = Billion Cubic Meters; 1 BCM = 1×10^9 m^3
While this figure is calculated at mean annual rainfall on 329 MHa, there may be variations in this on at least two counts: (1) 1,170 mm is a gross average for a continent-sized country and rainfall has huge inter-year variability; and (2) there are bound to be carry-overs and overdrafts between two consecutive years.

(2) Non-crop and Rain-fed Evapotranspiration (ET): As much as 19.25 % (63.34 MHa) of India’s geographical area is covered by forests. Trees, shrubs and other vegetative growth in these forests, as well as elsewhere, require water for evapotranspiration (ET) throughout the year, unlike in the case of agricultural vegetation, which requires water only during specific and intermittent periods. This nonagricultural ET also contributes significantly to the use of ‘unaccounted’ water resources of the country. A large portion of India’s cultivated area (roughly two-thirds) continues to be rain-fed. Evopotranspiration from the rain-fed crops, not included in the blue-water accounting, also forms part of the ‘unaccounted’ water.

(3) Deep Percolation: The ‘unaccounted’ water resources of India include percolation to very deep aquifers from where lifting water is either technically not feasible or economically viable. However, it is important to note that in certain areas (such as in north Gujarat), farmers have already started using even some of this ‘unaccounted’ water by using deep tubewells and submersible pumps. The total groundwater draft in such cases exceeds the annual replenishable recharge of the region and the phenomenon is, therefore, termed as ‘groundwater mining’.

(4) Sub-surface flows to Oceans: India has a 7,000 km. long coast line where, beneath the surface, fresh water meets saline water to form an aquifer-ocean interface. It is important to maintain a higher hydraulic head at this interface to prevent saline-water ingress into the sweet groundwater aquifer. This means that, at all times, there should be a continuous flow towards the lower hydraulic head and into the ocean beneath the ground. This accounts for the remaining ‘unaccounted’ water.

Utilizable Water Resources

Out of the 1,953 BCM, only about 1,086 BCM is actually usable. This ‘second deduction’ is because of the spatiotemporal variations in the water’s availability. The Ganga-Brahmaputra-Meghna (GBM) basin, which covers 33 % of the land area, accounts for more than 60 % of India’s water resources. Similarly, catchments of west flowing rivers, which cover only 3 % of the land area, account for 11 % of water resources. Thus, 71 % of India’s water resources are available to only 36 % of the area (at a comfortable 24 BCM /Mha[6]) while the balance 64 % area gets the remaining 29 % of the water resources (at 5 BCM /Mha). Moreover, about 80 % of the Himalayan river flows and 90 % of the peninsular river flows occur during the 4 monsoon months. While some of this gets used ‘online’, what remains needs to be stored ‘offline’ for use in the remaining 8 months.

After taking into account these variations, the ‘utilizable’ water resources of the country add up to 1,086 BCM; of which 690 BCM is the utilizable surface water potential and 396 BCM is the utilizable groundwater potential (Figure1) In a nutshell, therefore, if we look at the hydrological cycle as a system, the purpose of all water resource development interventions (large or small) is to use through the creation of ‘artificial delays,’ the water (at least once and as many times as possible) from the time it falls as rainfall to the time it flows into the oceans and comes back in the form of rain in the next cycle. Unless such delays are introduced into the hydrological cycle, our capacity to utilize our water resources will remain significantly diminished.

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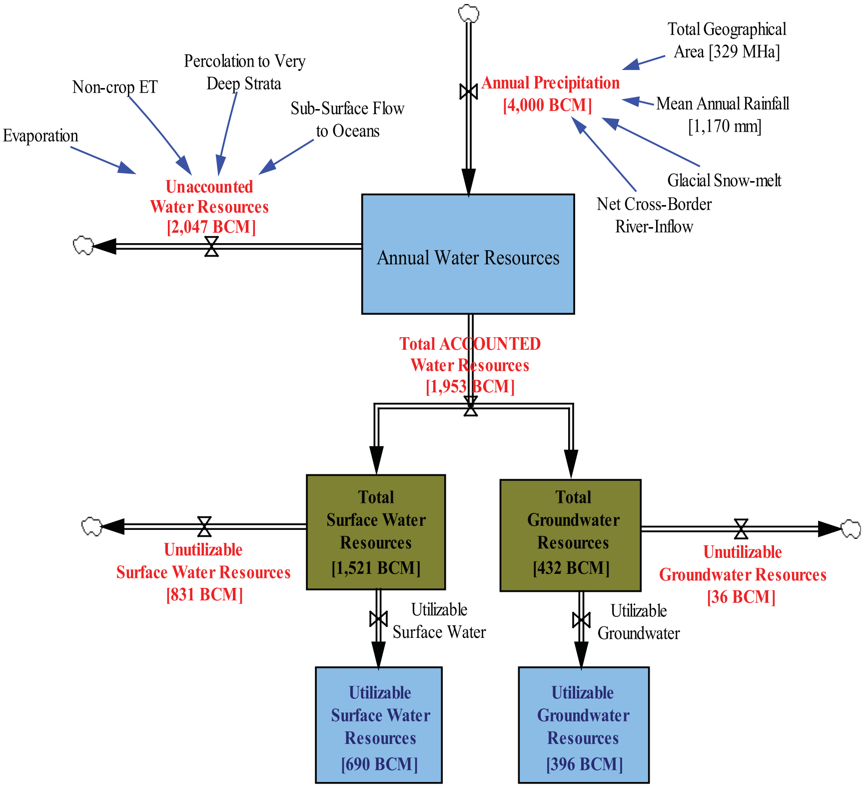
[6] Mha = Million Hectares

Figure 1. India's water resources.



NCIWRD's Vision of India in 2050

Water Provision for Irrigation

For estimating agriculture water use the projected requirement has been broken down into four key determining variables: (1) requirement for food production; (2) requirement for non-food production; (3) water use efficiency; and (4) land productivity.

The key assumption in estimating the irrigation requirement for food production has been that India will continue its policy of attaining self-sufficiency in food production. The commission also assumes that the present ratio of the area under food and non-food production (70:30 for irrigated areas; 66:34 for unirrigated areas) will remain constant. Interestingly, a comparison of projections made under a special study commissioned by the NCIWRD (Ravi 1998) with those by Bhalla and Hazel 1998 shows that even at 5 % growth rate of expenditure, the food and feed demand projected by the commission is less than that estimated by Bhalla and Hazel. Moreover, Bhalla and Hazel estimate that 42 % of India's population will be living in urban areas as early as 2020. Ravi's prognosis, however, estimates a much lower proportion of urban population for the same time period and has generated three scenarios of food demand under 4.0 %, 4.5 % and 5.0 % growth rates in expenditure. The commission has accepted the projections made by Ravi with the assumption of 4.5 % growth in expenditure to estimate their food and feed demand in 2010, 2025 and 2050.

Based on these, the commission has calculated the total water requirement for irrigation in 2010, 2025 and 2050 under low as well as high population growth scenarios as shown in Table 1.

Table 1. Water requirement for irrigation 2010, 2025, 2050 (BCM).

Variable	Remarks and Assumptions	Units	2010	2025	2050
Population	Low growth scenario*	Million	1,156.60	1,286.30	1,345.90
	High growth scenario**	Million	1,146.00	1,333.00	1,581.00
Urbanization	Low growth scenario	%	32	37	48
	High growth scenario	%	34	45	61
Per capita food demand	at 4.5 % expenditure growth	Kg/Cap/Yr.	194	218	284
Food plus demand	Low growth scenario	MT	245	308	420
	High growth scenario	MT	247	320	494
NSA	Marginal increase	Mha	143	144	145
GIA/GSA	Low growth scenario	%	40	45	52
	High growth scenario	%	41	48	63
Cropping intensity	20 % growth assumed over 50 years	%	135	140-142	150-160
% Food crops	Rain-fed areas (no change)	%	66	66	66
	Irrigated areas (no change)	%	70	70	70
Food crop yields	Rain-fed areas (modest increase)	T/Ha	1.10	1.25	1.50
	Irrigated areas (modest increase)	T/Ha	3.00	3.50	4.00
Food plus production	Low growth scenario	MT	246	307	422
	High growth scenario	MT	249	322	494
Irrigation efficiency	Surface water irrigation	%	40	50	60
	Ground water irrigation	%	70	72	75
GIR [NIR = 0.36]	Surface water irrigation		0.91	0.73	0.61
	Ground water irrigation		0.52	0.51	0.49
SW dependence	Growing dependence on SW assumed	%	47	49-51	54.3
Total water required	Low growth scenario	BCM	543	561	628
	High growth scenario	BCM	557	611	807

Source: Adapted from various tables (NCIWRD 1999)

Notes: * Based on United Nations 1995 projections
** Based on Visaria and Visaria 1996

Water Provision for Domestic Use

The commission has reviewed various norms suggested for water requirement for human use and has suggested a target of providing 220 liters per capita per day (LPCD) for urban areas and 150 LPCD for rural areas by 2050. On the basis of these targets, it has estimated the water requirement for domestic use under high and low population growth scenarios. It has further assumed that roughly 55-60 % of the water requirement for domestic use will be met from surface water sources. The total bovine water requirement for 2010, 2025 and 2050 has been estimated assuming a 0.5 % annual growth rate of bovine population and water requirement of 18-30 LPCD (Table 2).

Table 2. Estimation of domestic and municipal use and bovine requirements in 2010, 2025 and 2050.

Population type	2010	2025	2050
Targets for domestic and municipal use (LPCD)			
Class I cities	220	220	220
Class II-VI cities	150	165	220
Rural areas	55	70	150
Low and high projections (BCM)	42-43	55-62	90-111
% from surface sources (approx.)	55	57	60
Bovine water requirements (BCM)	4.8	5.2	5.9

Source: Adapted from Tables 3.26 and 3.27 (NCIWRD 1999)

Water Provision for Industrial Use

The commission, on its own admission, is tentative about its projections for water use in industries. It notes that there is a serious dearth of information and analysis on both present water requirement and future growth of industries in India. In such a scenario, it uses data available with the Central Pollution Control Board (CPCB) and the classification of industries into 17 sub-sectors done by the Planning Commission to arrive at its estimates. The estimates for the years 2010, 2025 and 2050 are 37, 67 and 81-103 BCM, respectively. These estimates are based on a 'sliding scale' with the lower estimate of 81 BCM arrived at by assuming significant breakthroughs in the development and adoption of water saving technologies for industrial production. It has further assumed that 70 % of these requirements will be met from surface water sources.

Water Provision for All Other Uses

In addition to the above, the commission has estimated water requirements for power generation, development for inland navigation, compensating evaporation losses from reservoirs, floods and environment and ecology. We briefly enumerate these below:

(A) Power Generation: While recognizing the growing importance of nonthermal sources, specifically hydropower, the commission contends that, in view of the economies in power generation from coal and the high initial investment and long gestation period in the construction of hydro-schemes, thermal power will continue to be the mainstay of India’s power sector in the foreseeable future. Based on estimates collected from various sources for thermal power and by using lump-sum provisions based on 9 % annual growth assumption for hydropower, it has used a water requirement norm of 0.001 BCM/100 MW power generation capacity. Based on this ballpark number and projections about India’s growing power generation capacities, the commission has arrived at its final results (Table 3).

Table 3. Water requirement for power development 2010, 2025 and 2050 (BCM).

Category	Norm for water requirement (0.001 BCM/100 MW)					
	2010		2025		2050	
	Low	High	Low	High	Low	High
Thermal	2.81	3.43	7.85	9.59	28.71	35.07
Hydropower*	15.00	15.00	22.00	22.00	30.00	30.00
Nuclear	0.29	0.36	1.13	1.38	3.68	4.50
Solar/wind	0.00	0.00	0.01	0.01	0.04	0.04
Gas-based	0.02	0.02	0.06	0.07	0.18	0.22
TOTAL	18.10	18.80	31.10	33.10	62.60	69.80

Source: Adapted from Table 3.28 (NCIWRD 1999)

Note: * Lump-sum based on 9 % annual growth assumption.

(B) Development of Inland Navigation: Of the 900 billion tonnes km per annum of the total inland cargo, only one billion tonnes is currently moved by inland waterway transport. The flow requirements in water channels are mostly expected to be met by seasonal flows in various river systems and canals. However, in the event of the damming of entire river flow, some water would be required to be released from upstream reservoirs for keeping the waterways navigable, especially during the lean season. In view of this, the commission has projected 7, 10 and 15 BCM surface water requirements for 2010, 2025 and 2050, respectively, for navigational purposes.

(C) Compensating Evaporation Losses: The loss due to evaporation from surface water reservoirs would depend on the reservoir geometry (surface area), water available in the reservoir and potential evaporation. For all practical purposes, evaporation from a water body is generally expressed as a percentage of the reservoir capacity[7]. However, such calculations would require reasonably accurate withdrawal data from all reservoirs. In the absence of such information, the commission has adopted an alternative method which is based on the live storage capacity. It has estimated national average values of evaporation losses from reservoirs as 15 % of the live storage capacity for major and medium irrigation reservoirs and 25 % for the minor irrigation reservoirs (Table 4).

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[7] The technical advisory committee of the NWDA has prescribed a norm for estimation of evaporation losses as 20 % of total withdrawals from the reservoir.

Table 4. Estimates of evaporation losses in 2010, 2025 and 2050.

Particulars	1997	2010	2025	2050
Live capacity (major storages)	173.73	211.44	249.15	381.50
Evaporation (at 15 %)	26.10	31.70	37.40	57.20
Live capacity (minor storages)	34.70	42.30	49.80	76.30
Evaporation (at 25 %)	8.70	10.60	12.50	19.10
Total evaporation loss (rounded-off)	35.00	42.00	50.00	76.00

Source: Adapted from Table 3.29 (NCIWRD 1999).

(D) Floods, Environment and Ecology: This is perhaps the most intriguing section of the entire chapter on water requirement projections. The commission makes a case for setting aside some water capacity for moderating the releases from dams in the event of high floods. However, it concludes that since such situations are 'casual' in nature, there is no provision made for such purpose. In any case, the requirement for flood control is for water storage capacity and not for additional water *per se*.

The commission report also talks at length about the poor state of the environment in the country, citing indiscriminate depletion of forest cover. It also mentions that India's forests can sustainably provide only about 0.041 BCM of fuel wood every year compared with the current demand for 0.240 BCM. Further, it adds that the industrial wood requirements are more than twice the current silvicultural productivity; and also that while the carrying capacity of forests is only 31 million head of cattle, currently about 90 million graze in forests. The report, however, concludes that most of the water requirements for aforestation would be met from precipitation and soil moisture (green water) and that there is no need for any specific earmarking for this purpose.

The commission notes the alarming levels of water pollution in India's rivers, giving examples of cities such as Delhi which produces nearly 2 billion liters of sewage, most of which is dumped untreated into the Yamuna River. It points out that for the treatment of sewage and for maintaining the river ecology (environmental flow releases – EFR), Delhi alone, would require about 3 BCM of fresh water to restore the quality of water to a safe limit. And yet, at the end, it makes 'a token provision' of 5, 10 and 20 BCM for water for all the purposes listed above for 2010, 2025 and 2050, respectively.

Total Water Requirement

Based on all the assumptions and projections above, the commission has estimated total water requirements under low and high demand scenarios as 629–694, 710–784 and 843–973 BCM for 2010, 2025 and 2050, respectively (Table 5).

As the maximum utilizable surface water resource amounts to only 690 BCM, the requirement in 2050, under high population projections, will exceed the availability according to the commission's projections. The same will be the situation in the case of groundwater resources where the maximum utilizable resource is 396 BCM and the projected requirement is

Table 5. Total water requirement 2010, 2025 and 2050 (BCM).

Uses of water	1997-98	Scenario	2010	2025	2050	%SW**
Irrigation	524	High	557	611	807	57-61
		Low	543	561	628	
Domestic and municipal	30	High	43	62	111	53-59
		Low	42	55	90	
Industries	30	High	37	67	108	70-71
		Low	37	67	81	
Power	9	High	19	33	70	77-81
		Low	18	31	63	
Inland navigation	-	High	7	10	15	100
		Low	7	10	15	
Environment	-	High	5	10	20	100
		Low	5	10	20	
Evaporation losses	36	High	42	50	76	100
		Low	42	50	76	
Grand Total	629	High	710	843	1,180	63-65
		Low	694	784	973	

Source: Adapted from Table 3.30 (NCIWRD 1999)

Note: **Proportion of requirement proposed to be met from surface water sources

428 BCM. The situation will be even worse when we take into account the spatial variation in demand and availability at the basin level.

Other Projections for Water Future 2050

Besides the NCIWRD projections, there are several other attempted projections regarding global and regional water availability and demand. A neat summary of several of these can be found in Strzepek 2001. While these efforts provide a sound body of knowledge to use as a sounding board for methodologies and approaches, the results are of a global nature and not specific for India. Seckler et al. 2000 and Rosegrant et al. 2002 have made global scenario building for water future 2025 where they have fairly specific forecasts and comments about India. We compare the three projections up to the year 2025 to provide the reader an overview of approaches, assumptions and broad results (Table 6). The broad conclusions of the three exercises are not remarkably different. Thus, irrespective of what one may wish to do about India’s water requirements, deny its size one cannot.

Table 6. Approaches, assumptions and broad results.

Aspects	NCIWRD (up to 2025)	Seckler et al. (BaU*)	Rosegrant et al. (BaU*)
Approaches			
Basic approach	Building blocks approach	Integrated, multi-year model	IMPACT-WATER model
Number of basins considered	24	Not specified	13
Whether trade considered?	No	Yes	Yes
Calculation of irrigation water requirement	Delta of 0.51 and 0.72 for ground and surface water, respectively	1cumt per kg grain	ET ratios for crops as per FAO.
Scenario building exercise	Not done except for high and low population growth	Subsequently tried out; Model permits scenario building exercise	Policy and lifestyle variables used to make 3 scenarios
Broad picture of India 2025	Tight overall balance; significant gaps and mismatches in several basins	Economic water scarcity: Investment needed for expanding primary water supply is unaffordable	Withdrawals will be 36 % of the renewable water resource; difficult to manage
Assumptions			
Annual available water resources	1,953 BCM	2,037 BCM	1,721 BCM
Efficiency assumption	0.50 for SW; 0.72 for GW	Basin efficiency gains assumed	Basin efficiency assumed to increase at specific rate
Domestic water requirement estimation	220 LPCD urban (Class I); 165 LPCD urban (Class II-VI); 70 LPCD rural	World Resources Institute (WRI) data used	(based on rural % and % HH with piped supply, income and prices of water) 41 BCM
Industrial water use	CPCB norms estimation	WRI data used very tentative	Water use intensity used along with estimates GDP growth
Livestock water requirement estimates	24 LPCD	WRI data used	FAO estimates used
Broad Results			
Population	1,286-1,333 million	1,216 million	1,352 million
% Rural	55-63 %	64 %	57 %
Projected irrigated area	67.00 MHa	63.10 Mha	76.00 MHa
Projected rain-fed area	77.00 MHa	81.00 Mha	68.00 MHa
Food grain requirement	308-320 MT	259 MT	275 MT

(Continued)

Table 6. Approaches, assumptions and broad results. *(Continued)*

Aspects	NCIWRD (up to 2025)	Seckler et al. (BaU*)	Rosegrant et al. (BaU*)
Approaches			
Water required for food production	561-611 BCM	702 BCM	332 BCM consumptive; much higher withdrawals
Assumed total water supply	SW: 382 BCM GW: 432 BCM Total: 824 BCM	1,263 BCM	Not specified
Total Water Demand 2025	784-843 BCM	811 BCM	815 BCM

Source: NCIWRD 1999, Seckler et al. 2000, Rosegrant 2002

Note: * BaU = 'Business as Usual' scenario

Potential Deviations from Business-as-Usual

The commission's report presents a rare case when issues of such diverse nature, requiring such diverse expertise, have all been dealt together, and thus making it compelling reading for any concerned individual. Having said that, we believe that the estimates represent ultra-conservative 'Business-as-Usual' scenarios which, among other things, fail to take into account two things: (1) coping mechanisms of the people and demand responses to policy triggers; and (2) technological and social breakthroughs on the horizon. Several autonomous and induced changes, which will profoundly influence the course of India's food agricultural sector over the coming 50 years do not find a place in the data and projections made by the NCIWRD (at least in the part available in the public domain). We discuss some such potential deviations here.

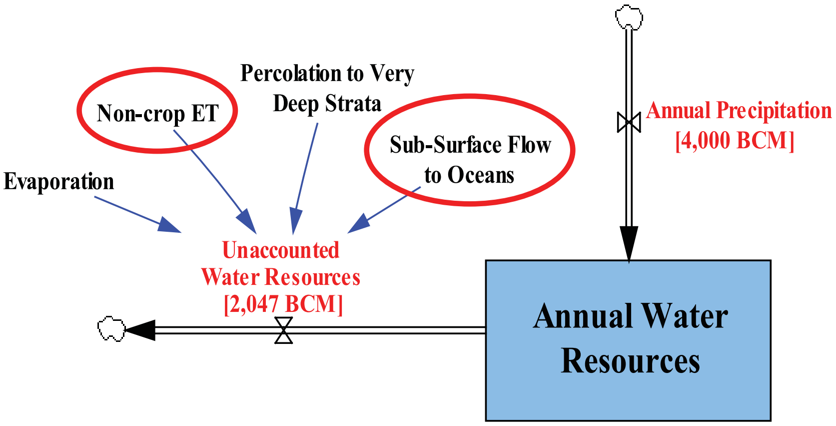
Rethinking Water Availability and Demand

(a) Accounting for Deductions at Source

The NCIWRD projections start with the assumption that the volume of water which can be put to use in India on a reasonably sustainable basis is 1,086 BCM (690 BCM of surface water and 396 BCM of annually replenished groundwater). As we have already explained above, the reduction from 4,000 BCM to 1,953 BCM is caused primarily due to four 'deductions-at-source': (1) Evaporation; (2) Non-crop and rain-fed ET; (3) Deep percolation; and (4) Sub-surface flows to the oceans. While little can be done to check evaporation and deep percolation, the other two 'deductions' can be seen as variables which are easily influenced by public policy and human actions (Figure 2).

Non-crop ET largely involves the water requirement by trees in the forests and naturally growing vegetation including grasslands, shrubs and weeds. While hardly anyone will want to suggest a policy to deplete forests to expand our utilizable water resource, how this will change in the coming 50 years needs to be looked at carefully. If our forests continue to deplete and degrade as they have in the recent past, much more of this water

Figure 2. Human influence on 'deductions-at-source'.



will be available for alternate uses, though at huge ecological costs. If, on the other hand, effective forest protection policies and laws coupled with efforts towards large-scale aforestation are going to move the country towards the universally preferred norm of 33 % forest cover (from the existing 20 %), much less water might actually remain utilizable. Both these scenarios need to be built into a realistic projection of India in 2050. The current projections made by the commission conveniently assume away any additional allocation for aforestation efforts citing that such requirements would be met by natural precipitation (green water). However, the fact that these might impact total blue water availability itself, is ignored[v].

(b) Which Water to Harvest Where?

Decentralized rainwater harvesting and groundwater recharge movements have become a contentious issue in India. The Rajasthan Government took strong exception to Tarun Bharat Sangh's *Laava ka Baas* dam, arguing that it was capturing the water which would normally have flowed down to Bharatpur. There are also reports about how 'indiscriminate' rainwater harvesting in the upper catchment is preventing the Jayakwadi Reservoir in Maharashtra from filling (Pandit 2004). Even in Saurashtra, home to what is perhaps the largest people's movement of its kind in the world, doubts have been raised that the popular water harvesting and groundwater recharge movement might have affected the storage in reservoirs downstream.

As the battle of wits between the 'bare-foot' and the 'suited-booted' engineers assumes alarming proportions, it is critical to make an objective assessment of the potential of such practices. The first question, of course, is – what water do these movements harvest

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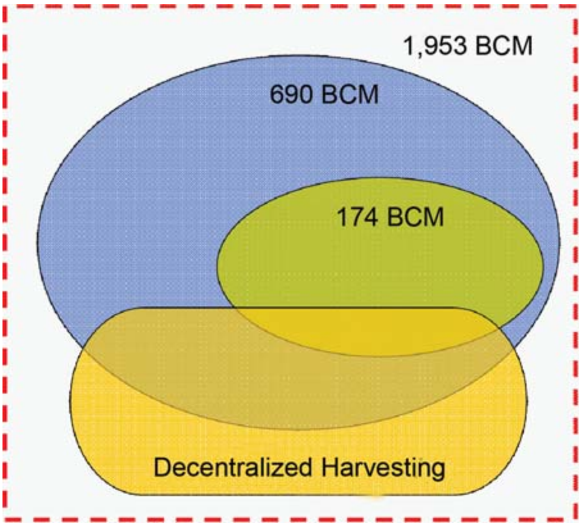
[8] While the importance of forests can hardly be overemphasized, there is a striving for better understanding of the relationship between forests and water in order to give forests their due place in water resource planning. Our argument here is not for or against forests but that water requirements of forests, and other ecological and environmental needs, must be given their due share in water resource planning.

Figure 3. Decentralized water harvesting: Which water? Where?



(Figure 3)? If the water captured and harvested by these movements is part of the 2,147 BCM which was anyway 'unaccounted', such conflicts should not arise. If we assume that the capture is from the 1,953 BCM 'accounted' water, then, can decentralized water harvesting and recharge contribute to increasing the utilizable surface water potential beyond 690 BCM? If only a maximum of 177 of the 1,869 BCM of water is so far stored in large, medium and minor dams (existing storage capacity), one would tend to believe that there's a lot of scope for decentralized structures to capture more, provided they are sited at the right places and are not built to capture the same water which would have been captured downstream anyway. What can we do to ensure this? Further, if the water harvested upstream is the same as would have been gathered by the existing storage facilities, there is a need to make a critical evaluation of the benefits derived from the water harvested upstream. Is the efficiency of water use higher in the decentralized water harvesting systems or would the same water have produced greater welfare if captured downstream by existing storage facilities (Verma 2008; Verma et al. 2008b)? Answers to these questions can also significantly change our prognosis of India 2050.

(c) Desalination: How Much Freshwater Can It Add (and at What Cost)?

The problems of drinking water in class I cities are quite common around the country. These have perhaps been most severe in Chennai where inspite of municipal supplies, a portion of the population have shifted to local private players for meeting their drinking water and domestic water requirements. A 20-liter *jerry can* of potable water costs around Rs. 10-12 and is commonly home delivered throughout the city. In 2004, the Finance Minister announced the setting up of a 1,000 crore desalination plant in Chennai which would have the capacity to supply 300 million liters of water in the city. Does this mark the beginning of a series of such projects dotted all along the 7,000 km long coastline of India? How much will these add to India's freshwater resources (and at what cost)? Alternately, what kind and level of inter-basin transfers will be required to meet the growing needs of cities and towns in the future[9]? Such questions also need to be addressed for a more nuanced prognosis.

(d) Re-use of Wastewater for Agriculture: Boon or Bane?

Domestic and industrial wastewater in most Indian towns and cities is disposed of without any treatment. Increasingly, farmers in peri-urban areas have taken to using untreated wastewater for irrigation. In some of the class I cities in India, the peri-urban water economy may approach the size of a mid-scale irrigation system, helping peri-urban farmers to improve their incomes and livelihoods (Bhamoriya 2004; Buechler and Devi 2003). However, using untreated wastewater can produce adverse health effects – direct, through farmers handling untreated wastewater, and indirect, through the consumption of food stuff irrigated with wastewater. The critical questions to address are (1) by how much can the re-use of domestic and industrial wastewater multiply India's fresh water resources?; (2) how quickly will these economies grow?; and (3) what would be the implications of agriculture wastewater on public health?

(e) Water Requirements vs. Water Demand

The commission's approach ignores the impact of two key variables on demand – the price at which water is supplied; and the quality of the supply. The commission's estimates of 'water demand' are built on the basis of minimum norms set down by various agencies. For example, the commission's estimates of water demand are based on the 220 LPCD and 150 LPCD norms. However, these can hardly be termed as 'demand'. In textbook economics, we find a definition of demand very different from the one assumed here.

Demand is defined as the desire to possess a commodity or make use of a service, combined with the ability to acquire it. In other words, it is the amount of a commodity or service that people are ready to buy for a given price. The commission's definition of demand, however, completely misses the ability and price aspects of demand. Certainly, if the assumption of the commission is that domestic water will be supplied at zero (or almost zero) price, the estimates are perhaps correct. However, such a policy is likely to lead to wastes of the order which an economy facing water scarcity cannot afford. If, on the other hand, the assumption is that 220 LPCD will be actually 'demanded' at a reasonably high price and at a given level of

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[9] There already exist examples of canal projects (near Mumbai, Ahmedabad and several cities) which, under pressure of growing metropolitans have been forced to divert water (initially planned to be used for irrigation) to meet domestic and municipal requirements. While the priority accorded to domestic use is hardly debatable, it indicates that the growing needs of cities were not taken into account while planning the command area of irrigation projects. Recent studies suggest that within the next 3 years, half the world's population will be living in cities. The NCIWRD projections based on Ravi 1998 estimate that such a situation will not happen in India even in the year 2050.

quality of supply, the issues become completely different[10]. Price and scarcity also prompt people to make adjustments in their consumption patterns. The same happens in irrigation water demand through changes in cropping patterns (shift in favor of less water intensive crops) and cropping systems (adoption of water saving irrigation practices and technologies). None of these things have been factored into the commission's building block approach.

A refined prognosis of India's water future must, therefore, account for two critical variables missed by the commission: (1) water demand (as against water requirement) as a function of price, availability and quality of supply; and (2) coping mechanisms of the users of water.

India's Demography 2050

(a) Incorporating the Possible Impact of HIV/AIDS

The commission reviewed some of the existing demographic estimates (Table 7) and chose, for reasons not clearly specified, to follow Visaria and Visaria 1996 estimate as 'high variant' (1,581.00 million) and the United Nation's 1994 estimate (UN 1995) as 'low variant' (1,345.90 million). Interestingly even the UN has, since then, revised its own estimates and their latest (2002) projections for India in 2050 are 5-8 % lower than those in 1994. There is a strong

Table 7. Projections of India's population growth.

Reference	All India population (in million)				
	2000	2010	2020	2025	2050
Natarajan 1993	1,020.50	1,183.10	1,301.00		
United Nations 1994					
(a) Low variant	1,013.50	1,156.60	1,249.70	1,286.30	1,345.90
(b) Middle variant	1,022.00	1,189.00	1,327.10	1,392.00	1,640.00
(c) High variant	1,030.50	1,221.70	1,406.10	1,501.50	1,980.00
Registrar General 1996	997.00	1,162.00			
Visaria and Visaria 1996	995.00	1,146.00		1,333.00	1,581.00
United Nations 2002					
(a) Low variant	1,016.94	1,145.90	1,236.09	1,265.61	1,241.56
(b) Middle variant		1,173.81	1,312.21	1,369.28	1,531.44
(c) High variant		1,201.71	1,388.48	1,474.48	1,870.06

Source: NCIWRD 1999, UN 2002

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[10] At a prominent gathering of water sector experts, Sunita Narain, head of the Centre for Science and Environment (CSE), made a strong pitch against the 220 LPCD norm. She argued that countries in the 'West' are targeting 125 – 150 LPCD for their cities by cutting losses and reducing wastage. Much of the 220 LPCD that gets delivered in Delhi (for instance) never reaches the consumers. Improving the quality of supply and the distribution system would bring down this requirement significantly.

possibility, therefore, that the reality in 2050 might significantly deviate from the commission's estimates. One of the reasons for such a deviation could be the potential impact of HIV/AIDS, which most population projections in India have so far ignored. Back in 1999, when the commission was preparing its estimates, the Government of India (GOI) had not officially recognized the emerging threat of HIV/AIDS. Today, not only has the situation perhaps somewhat degenerated but the GOI too has admitted that there are more than 5 million HIV/AIDS affected persons in the country[11].

Dyson and Hanchate 2000 are among the few who have attempted with and without AIDS projections. They argue that because the disease has a very long incubation period, the population known to be suffering from AIDS at any point of time represents only the tip of the iceberg. Further, they assert that while the effect in India might not be as dramatic as in some African countries such as South Africa, to make no allowance for its impact is no longer tenable. India must be looked at as a continent (like Africa) where there might be pockets (like South Africa and Botswana), which will be severely affected by the epidemic as well as pockets (like North Africa) where the level of infection will be low. Even in such large and diverse populations, the impact of HIV/AIDS on mortality rates and life expectancy can be significant. Between 1980 and 2005, it is believed that Africa's life expectancy will remain constant at around 51 years. However, in a 'without AIDS' scenario, it would have been roughly 5 years higher (UN 1999a; UN 1999b). In the light of the above, a closer re-examination of India's demography in 2050 is in order.

(b) Water Resources Planning in the 'Urban Century'

Even as the share of agriculture in the GDP of developing countries is continuously falling, the majority of their populations continue to depend on agriculture. This means that the water intensity of rural livelihoods has remained high and much of the planning for water resources has remained significantly agriculture-centric. However, recent trends in urbanization indicate that this is going to change sharply over the next half-century. Based on an analysis of the United Nation's latest demographic projections (UN 2002), Mohan and Dasgupta 2004 assert that the twenty-first century is going to be the 'Asian urban century' (Figure 4).

For India, this would imply that, by 2030, more than 40 % of her population will live in urban settings resulting in a further intensification of the already evident conflicts between towns and their hinterland for water. While urban water requirements total up to a small share in total fresh water use, and will perhaps continue to remain that way, year after year, knee-jerk policy action is taken to avert urban water crises. These annual bouts of crises and the fact that numerous irrigation systems are today unable to serve rural areas as their water gets diverted to cities illustrate that the growing needs of urban centers were not adequately considered at the time of planning the irrigation systems. Scenarios of urban water needs, which are backed by policy priority, much higher ability to pay, and often a stronger political pull, therefore must be developed and built into the planning process.

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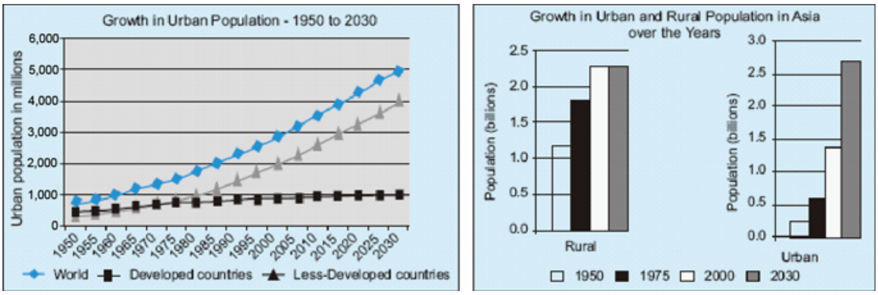
[11] Health Minister's reply to a question raised in Parliament on August 18, 2004.

Figure 4. Asia in the 'urban century'



Source: UN 2002; Mohan and Dasguptha (2004)

Liberalization and Food Crop Preferences

The commission's projections about water requirements assume that the share of food crops in irrigated as well as unirrigated lands will remain constant at 70 % and 66 %, respectively. However, this needs to be re-looked in the context of recent and possible future changes. Changes currently underway in the international trade policy environment and India's policy response to these will have wide-ranging consequences for the agriculture sector and for food security in the short and long terms. Along with China, India is one of the biggest players in the world food market; not by virtue of the size of their current trade, but on account of the potential havoc these countries can create by entering the world food market either as significant importers or exporters. If either of them decides to export or import in large numbers, world food prices could soar or crash in no time. With liberalization in trade, such situations will bring different incentives and signals to the Indian farmer. If world food prices are lower than the costs of production in India (assuming that China adopts a food export policy), free trade and Chinese farmers could potentially crowd Indian farmers away from food-farming.

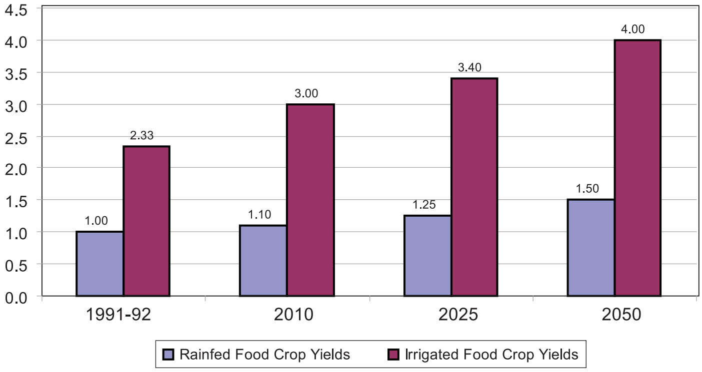
Three things will determine farmers' preference for food crops: (1) India and China's foray into the world food market and the resultant impact on food prices; (2) the degree of freedom and liberalization (conversely, support and protection) in international food trade; and (3) farm-level food surplus/deficit (it is not uncommon to see farmers being averse to buying food for self-consumption). While most people tend to agree that India will not give up its food self-sufficiency policy, individual farmers' decision to produce food crops will depend on price signals and market surplus/deficit conditions operating at the micro and meso level.

Modernization of Indian Agriculture

The commission has assumed a very modest increase in the productivity of irrigated and rain-fed food farming systems (Figure 5). If these assumptions hold, and given that total cropped area is unlikely to increase significantly, India would certainly need much more land under irrigation to feed the growing population. However, certain recent and potential future developments incline us to rethink.

Drip irrigation technologies promise 30–70 % improvement in water-use efficiency, besides offering significantly higher yields and several other benefits (Narayanamoorthy 1996; Narayanamoorthy 1997; INCID 1994; Magar et al. 1988; Kulkarni 1987). However, ever since

Figure 5. NCIWRD's projected yield growth.



Source: NCIWRD 1999

they were first introduced (some three decades ago), the area under drip irrigation has expanded rather sluggishly from 1,500 ha in 1985 to a little over 70,000 ha in 1992 (Chakravarty and Singh 1994) and rapid growth has only been seen in recent years as the area spread to 2, 25,000 ha in 1998 (Polak and Sivanappan 1998). However, this is still miniscule when compared with the estimated potential of 10.50 million ha (Sivanappan 1994). Despite active promotion by a growing private irrigation equipment industry and subsidies (up to 90 %) offered by the government, the appeal of these technologies has remained confined only to 'gentlemen farmers' (Shah and Keller 2002). Recent research suggests that when faced with groundwater stress; the same farmers who have rejected the capital intensive subsidized drip systems have innovated and embraced low-cost grassroots innovations such as *Pepsee* drips[12] which act as stepping-stone technologies. How quickly and to what scale will these technologies expand? What would be the net impact of 'more crop per drop'?

The impact of GM technologies, which for obvious reasons was not taken into account, could be another significant factor. So far, much of the debate on GM technologies in India has been concentrated around cotton rather than food crops. How the GM revolution can change the paradigms of food security needs to be studied in detail. Will future technologies offer seed varieties which will produce much more food grain for the same amount of water? What could be the implications of such technologies for the poor and for under-developed and developing countries? What kind of global system of governance will evolve to govern the GM revolution? Will intellectual property rights (IPRs) and patents play a big role in determining dominance in the global food business? What would all this mean for India?

Then, there are certain 'horizon' technologies like the system of rice intensification (SRI) which promise to improve water use efficiency. SRI is drawing attention world-wide as a compact of paddy cultivation practices that boost paddy yield while reducing water use and cost of

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[12] *Pepsee* systems are low-cost substitutes for drip irrigation systems made up of low density polythene ranging from 65 to 130 microns. At less than half the price of conventional drip systems, this grassroots innovation promises comparable results and has become very popular among cotton farmers in the Maikaal region of central India (Verma et al. 2004).

cultivation. Developed after over two decades of experimentation in Madagascar, under conditions not very different from those in India, SRI promises a significant increase in rice yields without the introduction of new varieties of HYV seeds or increase in external chemical inputs and, most importantly, with much reduced water use. This technology has been successfully tried with farmers in Sri Lanka, Tamil Nadu, Karnataka and Andhra Pradesh and by PRADAN with poor farmers in Purulia. In regions where paddy cultivation is central to rural livelihood systems, such as tribal Orissa, Jharkhand and Chattisgarh, SRI holds out a big promise that needs to be vigorously explored (Verma and Phansalkar 2004). Though there is little empirical data on SRI in India, data from other countries suggests it might become the mainstream practice in the years to come and could well be the 'next-big-thing' in rice cultivation. In Madagascar, average paddy yields among adopter farmers rose from 2 to 8 tonnes/ha. Is the promise offered by SRI too good to be true? Can such high yields be sustained in the long-run without affecting soil fertility?

Efficiency and Productivity Gains

(a) The Surface Irrigation Challenge

The efficiency levels at which surface irrigation projects work in most parts of the country does not require great elaboration. The Planning Commission contends that a mere 10 % increase in the efficiency of the existing irrigation infrastructure would lead to water supply to 14 million additional hectares of agricultural land[13].

The commission has projected that India's surface irrigation systems will work at 40, 50 and 60 % efficiency levels in 2010, 2025 and 2050, respectively. How these incredible efficiency gains will be achieved is mostly left to the readers' imagination. The commission has suggested that "all state irrigation acts have to be amended to incorporate provision for the formation of

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[13] In a series of exchanges between noted water sector stalwarts Ramaswamy R. Iyer and Radha Singh, in the Economic and Political Weekly, the latter remarked (Singh 2003):

> *"Conceding that the efficiencies of our water systems, especially irrigation, must be improved, the efficiencies within the major and medium sector (irrigation) are around 40 %, while in the minor and groundwater sectors it is above 60 %. With a delta of 0.95 m, total water use in major and medium irrigation sectors would be 37 MHa × 0.95 = 351 BCM. Improvements in efficiencies within this sector would render an additional availability of approximately 52 BCM which, though significant, is hardly enough to counter the widespread scarcity prevalent in numerous basins of our country."*

It is not clear as to how the figure of 52 BCM has been arrived at. If 351 BCM is taken to be a correct estimate, and assuming that surface irrigation projects do operate at 40 % efficiency level (which is the level that the commission projects India's surface irrigation projects will achieve by 2010), it would mean that the amount of water which actually reaches the farmers' fields would be 351*0.40 = 140.40 BCM. Assuming that no additional surface irrigation projects are commissioned, with improvement in efficiency from 40 % to 60 %, this should change to 351*0.60 = 210.60 BCM. The additional availability, therefore, can be calculated as 210.60 - 140.40 = 70.20 BCM. Again using the commission's own assumptions of water required to grow food grains, this additional 18.20 BCM water (which we just now discovered; 70.20-52) would amount to an additional food production of roughly 12 million tonnes!

farmers' bodies." It then proceeds to review performance of user managed irrigation systems in nine major states and concludes that their performance is far from satisfactory. Irrespective of the above, it hails the fact that over 25,000 water users' associations (WUAs), covering 5.8 Mha, have been created in various states.

Initiating a program for the user management of irrigation systems or the mere formation of irrigation communities will not automatically lead to improved efficiency in surface irrigation systems. One school of thought argues that even when successful, participatory irrigation management (PIM) only can help improve distribution efficiency, which, in any case, is only a small part of the overall efficiency[14]. Proponents of this school argue that the main culprit in poor efficiencies is the poor 'Main System Management'. Factors such as lower water availability, untimely and unreliable supply, lower storage capacity and higher conveyance losses vis-à-vis those assumed at the planning stage, are responsible for poor efficiencies. The pertinent questions, therefore, are: what kind of efficiency improvements (CE or DE or AE) can we achieve by 2050?; How, how much, and at what cost? To what extent will PIM or irrigation management transfer (IMT) salvage India's public irrigation systems? Is there a need to think of and experiment with alternative strategies and institutional arrangements for vitalizing this important sector?

(b) Relative Dependence on Surface and Groundwater

To us, there seems to be a distinct 'surface water bias' in the commission's estimates. It assumes that surface water will be used to meet 57–61 % agricultural; 53-59 % domestic and municipal; 70–71 % industrial; 77–81 % power generation; and 100 % of all other requirements. Recent studies, however, indicate that groundwater might be contributing much more than is commonly understood. While the commission estimates that the total groundwater use in 2010 will only be around 230 BCM, recent estimates of present groundwater use already exceed this number. According to the Central Ground Water Board (CGWB 1995), the groundwater provision for domestic, industrial and other (nonagricultural) uses totals to 71 BCM. If we add to this, the estimate for groundwater use in agriculture by Shah et al. 2003, 210 BCM, the total groundwater use in India can be estimated as 281 BCM. Thus, in all, anywhere between 250 and 300 BCM of groundwater is currently being used[15]. Compared to this, the commission estimates that total groundwater use in 2010 will be around 230 BCM.

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[14] According to the International Commission on Irrigation and Drainage (ICID), Overall Efficiency (E) = CE * DE * AE where,
CE = Volume of water delivered to the distribution system / Volume of water delivered at the canal head;
DE = Volume of water delivered to the field / Volume of water drawn from the distribution system;
AE = Volume of water made available to crops / Volume of water drawn at the field head.

[15] Here, it is important to note that a part of the groundwater use is caused not directly by rainfall recharge but by the return flows from irrigation caused by the inefficiencies in irrigation. However, the degree of this overlap is difficult to measure and quantify.

Other Macro Variables

(a) Changes in India’s Macro Hydrology

With a predominantly agrarian economy and a 7,000 km long, densely populated, and low lying coast-line, the impact of climate change in India can be expected to be significantly higher than that suggested by the ‘token provisions’ made for by the commission. The most immediate impact of higher temperatures on India’s water resources would be in the form of higher rates of evaporation. Potential changes in temperature and precipitation might also have a dramatic impact on soil moisture and aridity levels of hydrological zones, besides changing evapotranspiration, runoff coefficients, river flows and groundwater recharge.

Research carried out by the Hadley Centre[16] indicates that the mean annual runoff in Brahamaputra would decline by 14 % by the year 2050. The Intergovernmental Panel on Climate Change has predicted a likely increase in the frequency of heavy rainfall in South Asia (IPCC 1998) and notes that the impacts of climate change in India will be felt more directly in the western Himalayas as the contribution of snow to the runoff of major rivers on the western side is about 60 % compared with 10 % on the eastern side (IPCC 2001).

How real and how significant will be the impact of climate change in the context of water resource availability and use? These potential implications need to be brought into the prognoses for India 2050.

(b) Virtual Water Trade and Food Policy

Much of the projections made by the commission are based on the assumption that India will continue to pursue its policy of food self-sufficiency. At present, much of India’s foodgrains are produced in a handful of states, all of which are facing water shortages and groundwater depletion. On the other hand, India’s water rich regions, such as states in eastern India, are importing food from these states since they are unable to produce enough to meet their requirements. If we view this inter-state food trade within India as trade in ‘Virtual Water’[17], we see that water-scarce regions in India are exporting virtual water to water rich regions, thereby exacerbating the water crisis. In part, this is due to the food procurement policies of the Government of India, which encourage states like Punjab and Haryana to grow foodgrains by offering them assured markets, lucrative prices and several input subsidies including those for electricity and fertilizers. On the other hand, farmers in water rich states are facing higher

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[16] www.metoffice.com/research/hadleycentre

[17] ‘Virtual Water’ refers to the volume of water needed to produce agricultural commodities. When a commodity (or service) is traded, the buyer essentially imports (virtual) water used in the production of the commodity. In the context of international (food) trade, this concept has been applied with a view to optimizing the flow of commodities considering the water endowments of nations. Using the principles of international trade, it suggests that water-rich countries should produce and export water intensive commodities (which indirectly carry embedded water needed for producing them) to water-scarce countries, thereby enabling the water-scarce countries to divert their precious water resources to alternative, higher valued uses (Allan 1998, Hoekstra 2003, Wichelns 2004).

input costs and are able to derive lower market prices for their produce. This has lead to a stagnant, low-input agriculture, resulting in sustained poverty. Some of the best water endowed states are also the poorest. If, however, food policies were to be re-aligned to favor water rich regions to encourage them to grow more foodgrains, India's food demand and supply scenarios would drastically change (Verma 2007; Verma et al. 2008a).

(c) Water Intensity of Rural Livelihoods

Agriculture continues to be the biggest absorber of people in India and even if food security concerns were to be met otherwise, people will continue to depend on agriculture for their livelihoods and, therefore, will continue to demand water for irrigation. It therefore becomes important to make studied projections as to what proportion of the country's population will continue to depend on agriculture through to 2050.

As of now, some 64 % of the population in the country derives its livelihoods substantially from agricultural operations: either as cultivators or as agricultural wage laborers. The share of agriculture in GDP has fallen to about 29 % nationally. This fall in share of agriculture in GDP is accompanied by a much smaller fall in the proportion of the people deriving their livelihoods from agriculture. For instance, agriculture contributes only 13 % to the state domestic product in Gujarat while it continues to support 45 % of the main workers. While on the one hand, this indicates the declining share of agriculture, it also perhaps indicates large-scale diversification in rural livelihoods.

The important questions to address are (1) How water-centric will rural livelihoods be in the future[18]?; and (2) Even if a large number of people move out of agriculture, would it mean a reduction in cropped and irrigated area?

The Emerging Agenda for 'Water Future' Research

While the conservative estimates of the commission paint quite a grim picture of India's water future, it must be granted that if no corrective action is taken, no forward planning is done and nothing is done to change the wasteful and inequitable use of water, the situation could well be like the one depicted by the commission. However, the broad statement of the demand and supply as made by the commission is only the canvass; the actual picture will emerge only with people responding to the crisis as they see it cropping up. The report thus offers a good base, a starting point, which needs to be worked and built upon, rather than accepting it as the last word. The authors of the report too were, perhaps, quite aware of some of the inherent drawbacks which might have resulted from the paucity of available data and analyses. That is why even the report itself does not shy away from categorically stating that:

> *"…These estimates should be treated basically as approximations…It would be desirable to review these estimates regularly, say, at the interval of 5-10 years."*

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[18] See Phansalkar 2005 for a detailed discussion on this issue.

Table 8 summarizes the foregoing discussion and presents a framework for 'water future' research. While each of these individual studies are important in themselves and may require a diverse set of expertise and competencies, on their own, they might not provide an overview of India's water challenge in 2050. A good prognosis, rather than suggesting definitive answers to how much water India will need in 2050, will generate alternate policy scenarios and sensitivity analyses. Which of the scenarios will be closest to the reality in 2050 will depend on the robustness of the assumptions and on the path India chooses to take over the coming decades.

Table 8. The emerging agenda for 'water future' research.

Theme	Studies	Issues
Rethinking water availability and demand	Managing 'deductions-at-source'	Adding 'accounted' water; forest-water linkages; non-crop ET; sea-water intrusion
	Decentralized water harvesting	Upstream-downstream conflicts; Which water to harvest and where?
	Desalination: How much freshwater can it add (and at what cost)?	Potential of desalination for meeting urban water requirements; costs of desalination
	Wastewater irrigation: boon or bane?	Wastewater economy; Direct and indirect health impacts of wastewater irrigation
	Will requirements expand to fill free supply?	Requirement-demand gaps; pricing and quality of supply; coping mechanisms
Demographic projections	Implications of HIV/AIDS	With and without, high and low HIV/AIDS scenarios
	Urban century	Urbanization trends in India and regional variations
Liberalization of food trade	Impact of world food trade on India's food security	WTO/GATT; food self-sufficiency policy; Chinese food policy; world food prices
Modernization of Indian agriculture	Water saving irrigation technologies	Potential and spread of drip and sprinkler technologies
	GM revolution	Impact of high productivity GM crop varieties
	Horizon technologies	Potential impact of horizon technologies such as SRI
Efficiency and productivity of agriculture water use	Surface irrigation efficiency	PIM/IMT; alternate institutional arrangements; CE-DE-AE
	Future sources of growth in India's water resources	Relative importance of surface and ground water
Macro Variables	India's macro hydrology	Climate change impact on evaporation, ET, Run-off, rainfall, agricultural productivity
	Virtual water trade and Food policy	Food self-sufficiency; food procurement policy; input subsidy concentration
	Rural livelihoods	Water intensity of rural livelihoods; occupational structure

One of the windfalls of the entire debate on NRLP has been a heightened interest among the scientific community in projections about 'India's water future'. Perhaps prompted by the estimates made by NCIWRD, there have been some attempts at the arguably difficult exercise of predicting the future. Irrespective of whether the river linking plan finally gets implemented or not, we believe that it provides an excellent opportunity for India to review its preparedness for meeting the challenge ahead. Admittedly, our analysis raises more questions than we attempted to answer but we hope that this will trigger a studied debate on this very important theme.

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Irrigation Demand Projections of India: Recent Changes in Key Underlying Assumptions

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Introduction

Coping with annual floods and droughts has been a major concern for India's agriculture in the past several decades. Concerns are more acute today as much of India's billion plus population depend on agriculture for their livelihood. Also, the slow growth of the agriculture sector, usually the hardest hit from floods and droughts, is a major constraint on the efforts to reduce rural poverty and also diversify and sustain the present economic boom. Annual floods on average affect more than 3 million ha of cropping area and 34 million people, mostly in the east, and inflict damage amounting to well over US$220 million. Droughts affect 19 % of the country, 68 % of the cropped area and 12 % of the population. Concerned on this twin menace, and responding to public interest litigation, the Supreme Court of India ordered the Government of India to expedite the interlinking of rivers plan, a series of large-scale interbasin transfers aimed at moving water from surplus basins to water short basins, before the first quarter of this century. A major factor in the 'National River Linking Project' (NRLP) as originally conceived is that it would ease water scarcities, especially for irrigation, due to droughts in the southern and western parts of India and mitigate the floods in the eastern parts of India and Bangladesh. However, although there has been some renewed efforts to implement components of the NRLP since the Supreme Court Decision, the NRLP is a very contentious issue today both within India and outside.

The significant irrigation water demand increases projected by the National Commission of Integrated Water Resources Development (NCIWRD) were a major facet of the initial justification of the NRLP (GOI 1999). The most prominent drivers of the NCIWRD irrigation demand projections were national self-sufficiency; nutritional security for all people; and rural livelihood security. However, even at that time the commission recognized that their projections were only a first approximation and would need periodic updating with the rapidly changing economic growth patterns.

The primary purpose of the paper is to re-examine the assumptions of irrigation demand estimation upon which the plans for the NRLP have been fashioned. The paper consists of three sections. Following this introduction, the second section investigates the recent trends of drivers affecting irrigated agriculture and assesses possible deviations from the NCIWRD assumptions. We conclude the paper by highlighting the key drivers which influence the short- to medium-term policy options for meeting the future irrigation demand.

Assumptions of Irrigation Demand Projections - A Re-examination

The National Water Development Agency (NWDA), the government agency responsible for implementing the NRLP project, states that "… for meeting the requirement of about 450 million metric tonnes of food grains the irrigation potential has to be increased to 160 million ha for all crops by 2050, and one of the most effective ways to increase the irrigation potential for increasing the food grain production, mitigate floods and droughts and reduce regional imbalances in the availability of water is the interlinking of rivers to transfer water from the surplus rivers to deficit areas..." (NWDA 2006). The NWDA message primarily summarized the implications of NCIWRD food and water demand projections, where the irrigation demand projections would expect to add another 34 million ha of surface irrigated area.

The NCIWRD projected water demand under high and low population projection scenarios (Paper 2). The plans for the NRLP were based on the 'high' population growth scenario. A major part, 68 %, of the NCIWRD high water demand projection (1,180 km^3), is for irrigation (GOI 1999). Key assumptions leading to the irrigation demand estimation are as follows:

- Food grain demand increase from 155 to 450 million tonnes. The total demand projection, including feed, seeds and waste, increases from 177 to 494 million tonnes. The Commission has assumed food grain self-sufficiency, and expected that food grain production would generate adequate income for the rural people.
- Irrigated and rain-fed grain yields, to grow 0.95 % and 0.71 % annually. Accordingly, irrigated and rain-fed yields are to increase from 2.3 to 4.0, and 1.0 to 1.5 tonnes/ha, respectively.
- The net irrigated area or the irrigable area increases from about 50 to 91 million ha; gross irrigated area from 68 to 146 million ha, and irrigation coverage of grain crops remains the same at 70 %.
- Surface to groundwater irrigated area ratio changes from 45:55 to 55:45.
- Net sown area remains the same at 142 million ha; gross crop area increases from 186 to 232 million ha; and grain crops cover 69 % of gross crop area. The latter assumption, an increase of 2 % from the 1993/94 level, basically maintains the dominance of grain production in Indian agriculture and a very slow growth of crop diversification.
- Surface irrigation efficiency increases from 35-40 % to 60 %; and groundwater irrigation efficiency from 65 to 75 %.

However, many of the above assumptions are either not in line with the trends since the time of the projections, or now seem to be rather conservative given the increasing scope for technology use in the Indian agriculture. Therefore, we re-examine the NCIWRD assumptions in line with the trends of the key-drivers observed in the 1990s, in what we refer to as the business-as-usual scenario. That is, what we expect to happen in the future, based on recent trends, past conditions, and no major changes in the policy environment.

Food Demand

The NCIWRD projection for food grain demand, which is equivalent to 778 g/person/day by 2050, is no longer valid on two points. First, this level of grain consumption provides a calorie supply of 4,000 kcal/person/day, which is even higher than the calorie intake in the developed countries with animal product dominated diet. For example, the USA ranked highest in calorie intake among the developed countries, consuming only 3,800 kcal/person/day. It is highly unlikely that, with a vegetarian centered diet, India will ever reach this level of calorie intake in the future.

Second, recent trends show, non-grain food crops and animal products in the diet are increasing (Table 1). The food-grain consumption per capita in both the rural and urban areas (Amarasinghe et al. 2007a) and in both upper and lower income groups (Joshi et al. 2007) is decreasing. The share of food grains in total calorie supply in India itself has decreased from 70 to 63 % between 1990 and 2000 (FAO 2005). Based on recent trends, it is estimated that total calorie supply will increase to 3,000 kcal/person/day by 2050, from 2,345 kcal/person/day in 2000 (Amarasinghe et al. 2007a). However, the share of calories met by food grains, non-grain food crops, and animal products will change from 65:28:8 % in 2000, to 48:36:16 % by 2050. In fact non-grain food crops and animal products will dominate the consumption pattern in the middle of this century.

Table 1. Changing food consumption and calorie supply pattern.

Crop or livestock product	Consumption (kg/person/year)			Annual growth (%)		Calorie supply (Kcal/person/day)			Annual growth (%)	
	1980	1990	2000	1980-1990	1990-2000	1980	1990	2000	1980-1990	1990-2000
Grain crops										
Rice	68	79	74	1.5	-0.6	670	780	737	1.5	-0.6
Wheat	46	55	58	1.8	0.5	390	467	491	1.8	0.5
Maize	7.4	7.7	4.8	0.4	-4.7	61	64	39	0.5	-4.7
Other cereals	28.9	23.3	16.8	-2.1	-3.2	248	200	144	-2.1	-3.3
Total cereals	150	164	154	1.0	-0.7	1368	1510	1412	1.0	-0.7
Pulses	13	14	12	1.1	-1.9	120	132	109	1.0	-1.9
Total grains	162	178	165	1.0	-0.8	1487	1643	1521	1.0	-0.8
Non grain crops										
Oil crops	22	28	40	2.6	3.6	152	195	273	2.5	3.4
Roots & tubers	4.9	4.6	5.4	-0.5	1.6	41	40	47	-0.3	1.7
Vegetables	48	53	67	1.0	2.4	32	35	44	0.9	2.3
Fruits	26	28	37	0.8	2.8	31	34	47	1.0	3.4
Sugar	20	23	25	1.3	0.8	193	221	240	1.4	0.8
Total non-grains						450	525	651	1.6	2.2
Livestock products										
Beef	2.4	2.7	2.6	1.2	-0.4	8.1	9.5	9.0	1.5	-0.5

(Continued)

Table 1. Changing food consumption and calorie supply pattern. *(Continued)*

Crop or livestock product	Consumption (kg/person/year)			Annual growth (%)		Calorie supply (Kcal/person/day)			Annual growth (%)	
	1980	1990	2000	1980-1990	1990-2000	1980	1990	2000	1980-1990	1990-2000
Pig meat	0.4	0.5	0.6	2.3	1.8	3.7	4.8	5.6	2.5	1.6
Goat/sheep	0.7	0.7	0.7	0.5	0.0	3.0	3.2	3.1	0.9	-0.4
Chicken	0.2	0.4	1.0	8.0	9.1	0.8	1.6	3.9	7.0	9.5
Milk/butter/ghee	40	55	66	3.2	1.9	93	129	153	3.4	1.7
Eggs	1	1	1	5.5	1.8	3	5	6	5.1	2.1
Fresh water fish	1	2	3	3.4	4.1	3	4	5	3.3	4.3
Total animal products						119	162	192	3.2	1.7
Total all items						2082	2366	2413	1.3	0.2

Source: FAOSTAT Database (FAO 2005).

Recent trends also indicate a diversifying consumption pattern. Among grain crops, preference for coarse cereals is decreasing fast. The consumption of maize and other coarse cereals declined from 4.7 and 3.7 % annually in the 1990s. Most importantly, the consumption of rice, a major staple food in the south and east, also declined, by 0.6 % annually in the 1990s. It is projected that per capita food grain consumption will further decrease in the future, from 472 kg/person/day in 2000 to 454 and 417 kg/person/day by 2025 and 2050, respectively.

Among non-grain crops, the consumption of fruits, vegetables and vegetable oils has increased significantly in the 1990s (Table 1). Combining the trends of increasing calorie supply of non-grain food crops and also the composition of the consumption of different crops, it is estimated that the consumption of vegetables, fruits, oil crops and roots and tubers per person has increased by 64 %, 68 %, 75 % and 112 %, respectively. In fact, non-grain crops are also expected to form a major part of the nutritional intake in the future.

Milk and milk products provide a major part of the animal product calorie supply at present. During the 1990s the consumption of milk has increased at a steady pace (1.7 % annually), and it has increased for chicken, eggs and freshwater fish significantly. It is expected that increasing income and urbanization will push the demand for animal products even further, increasing the consumption of milk by 51 % and fresh water fish by 142 % (Amarasinghe et al. 2007a). The consumption of chicken and eggs is expected to increase significantly, from only 1.0 and 1.4 kg/person/year respectively in 2000, to 13.4 and 34.1 kg/person/year, respectively over the period of 2000-2050.

Feed Demand

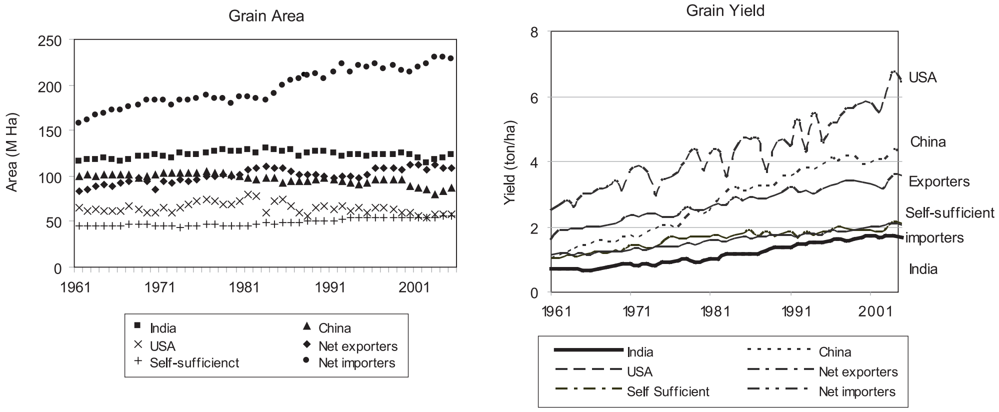
With the increasing consumption of animal products, especially of chicken and eggs, the demand of feed grains, mainly of maize, will increase significantly over the period of 2000 to 2050. The demand for feed grains is projected to increase, from 8 million tonnes in 2000 to 38 and 111 million tonnes by 2025 and 2050, respectively.

For feed demand, the commission projected 48 million tonnes, which significantly underestimates the present and future needs of livestock. Despite this, the total overall grain demand projections of the NCIWRD of 494 million tonnes is higher than the 377 million tonnes projected based on recent trends. The demand-driven, diversified agriculture pattern is transforming Indian agriculture (Joshi et al. 2007). This transformation will create numerous opportunities for increasing agricultural production, marketing, food processing, and retailing in the rural sector. The direct and indirect impact through agricultural diversification will not only help alleviate rural poverty, but also help increase the sustainable agricultural production systems in India (Barghouti et al. 2007; Pingali and Rosegrant 1995).

Crop Yields

The expected increase in yield is a major driver of additional irrigation demand. In fact, the NCIWRD assumption of annual growth in grain yields, 1.2 % and 0.7 % between 2000 and 2025, and 2025 and 2050, respectively, is a major point of contention in the recent discourse. The data indicate that India can be self sufficient in food grains without any additional irrigation if it doubles the crop yield in 50 years (Amarasinghe et al. 2007a). Many people argue that a great potential exists for doubling the crop yield (1.7 tonnes/ha in 2000), given what other large countries with similar irrigation growth have achieved over the last four decades (Figure 1). In fact, Figure 1 seems to suggest in general, those countries with a focus on exporting have given greater emphasis on yield growth to achieve production increase, whereas countries with policies aimed at self-sufficiency and net importers have emphasized more on expanding their area. Today, India has the world's largest area under grains with the largest irrigated area, but has one of the lowest yields among major crop-producing countries.

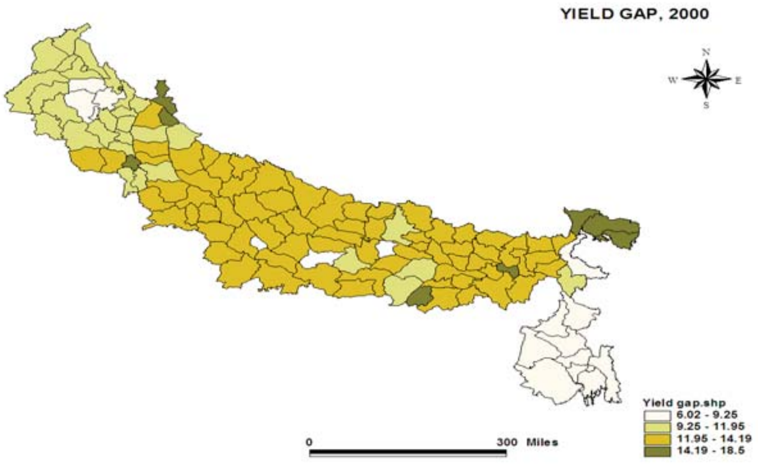
Figure 1. Growth patterns of grain area and yield in different countries or country groups.



Source: FAO 2005

Given the expansion of irrigated agriculture, it is puzzling that India was not able to match other countries in yield growth. According to official data, India has the largest irrigated area in the world (GOI 2005). However, studies show that crop yields vary in plots in the same farm, across farms in the same irrigation system, and across irrigation systems in similar agroclimatic zones etc (Kumar et al. 2006a, 2006b; Palanisami et al. 2006). Similarly, a significant gap exists between the actual and the potential yield in different agroclimatic zones (Figure 2, Aggarwal et al. 2000). The actual rice-wheat yields of 7.5, 6.1, 4.5, 4.4 t/ha, of Punjab, Haryana, Uttar Pradesh, Bihar and the West Bengal, are much below the potential yield of 12-19 tonnes/ha. Thus, studies claim that with proper water and nutrient management and advanced technology-use yield potential could be increased significantly.

Figure 2. The gap between the actual and potential yield of rice + wheat system in the Indo-Gangetic plain.



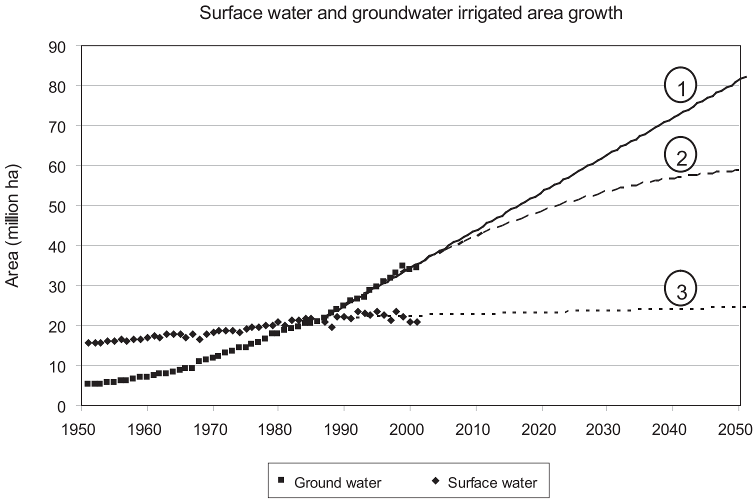
India also has the largest rain-fed crop area in the world with one of the lowest levels of rain-fed crop productivity. India's rain-fed grain yields (0.95 tonnes/ha) in 1995, is only one-fifth of the rain-fed yield in USA, one-third of China, and less than one-half of Argentina, Brazil and Australia (IWMI 2000). While favorable rainfall conditions were a major factor of high yields in other countries, low yield in rain-fed agriculture in India is mainly attributed to frequent occurrences of mid-season and terminal droughts (Sharma et al. 2006). The occurrence of mid-season or terminal droughts in 1-3 weeks of consecutive duration during the main cropping season causes either crop failure or low yield. However, a supplemental irrigation during the mid-season and terminal drought periods has the potential to improve the yields by 29 to 114 % for different crops. A district level analysis shows that as much as 25 million ha of rain-fed area (excluding extreme arid and wet areas) could benefit from supplemental irrigation during the water stress periods of the main season. This same area has approximately 99 km^3 of surface runoff that could be captured by rainwater harvesting, but requires only about 18-20 km^3 for supplemental irrigation. The supplementing of one critical irrigation to 18.75 m ha during a drought year and 22.75 million ha during a normal year could boost total rain-fed production by more than 50 %. Of course, the viability of implementing such a scheme on a landscape scale needs to be more closely examined.

In spite of the scope for improvements, the rate of growth in grain yield decreased in recent decades, from an all time high of 3.8 % annually in the 1980s to 2.1 % in 1990s. However, using conservative assumptions with regard to advanced irrigation technology, small-scale irrigation, groundwater use, enhanced water conservation, proper nutrient management, and investments in research and extension, Amarasinghe et al. 2007b concluded that irrigated crop yields could be increased at the rate of 1.4 % for 2000 to 2025, and 1.1 % annually from 2025 to 2050 in contrast with the 1.2 % and 0.7 % projected by NCIWRD for the same two periods.

Land Use Patterns

Groundwater has been the primary source of the growth in India's net irrigated area (NIA) in the last two decades, adding 8.4 and 8.6 million ha, respectively in 1980s and 1990s. In fact, the expansion in groundwater irrigated area has more than offset the decline of the surface irrigated area during the 1990s. The net surface irrigated area shrank by 0.9 million ha: from 22.0 million ha in 1989 to 21.1 million ha in 1999 (Figure 3). Given the present day investment patterns, groundwater development will most likely continue to drive the irrigation expansion in the near future.

Figure 3. Growth patterns of net surface and groundwater irrigated area.



Source: GOI 2004

Note: Lines 1 and 2 show the linear and quadratic extrapolation of net groundwater irrigated area using data from 1985-2003. Line 3 shows the linear extrapolation of the net surface irrigated area using the data over the same period.

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[1] The Government of India sets targets for increasing irrigated area in successive 5-year planning periods. The IXth 5-year plan, which covers 2002 to 2007, envisages adding 9.8 million ha through major and medium irrigation projects to the existing irrigation potential. The total net surface irrigated area created before the IXth plan is 21 million ha.

If net groundwater irrigated area continues to expand at the same rate as in the recent past, it would reach 80 million ha by 2050, and with a slowing rate of increase (quadratic growth), the net area irrigated by groundwater would reach 60 million ha. However, it is likely that the pace of expansion will slow down further due to constraints on the availability of the resource and the over-abstraction in many regions. Thus, given the recent trends and the constraints due to over-abstraction in some regions and the opportunities that exist in other regions, net groundwater irrigated area would increase from 34 million ha in 2000 to 50 million ha in 2050. It is also likely that most of the ongoing major and medium canal irrigation projects will be completed before 2025. In fact, the IXth irrigation plan[1] aimed at adding another 10 million ha to the net surface irrigated area between 2002 and 2007. Overall, the net surface irrigated area is projected to increase from 21 million ha in 2000 to 31 million ha by 2025, and remains at that level there after.

The projected increase in net groundwater irrigated area to 50 million ha and net surface (canal and tank) irrigated area to 31 million ha by 2050 will mean that the NIA supplied by ground and surface water will increase from 56 to 81 million ha. As a result of this expansion, the gross irrigated area (GIA) is projected to increase from 76 to 117 million ha and gross crop area (GCA) is projected to increase from 189 to 209 million ha between 2000 and 2050 (Amarasinghe et al. 2007b). These estimates are significantly lower than the assumption of NCIWRD scenario, which assumed that GIA and GCA would increase to 146 and 232 million ha respectively by 2050.

Another striking difference is that the business as usual trends project the surface to groundwater irrigated area ratio to reach 39:62 % by 2050, whereas the earlier NCIWRD estimates determine this to be 55:45 %. Under the NCIWRD surface water is the source of choice for 60 % of the additional GIA, whereas under the prevailing trends the business as usual scenario determines that groundwater will be a dominant source for 61 % of the additional irrigated area. In the latter case, the essentially private-sector driven groundwater sector would continue to play the dominant role in India's irrigation futures. However, this scenario would lead to severe groundwater depletion in many regions (Amarasinghe et al. 2007b). The major challenge facing the water sector in India today and over the long term is how to increase the groundwater stocks (supply enhancement) to arrest the declining groundwater tables, and how to sustain water use by minimizing uncontrolled groundwater pumping (demand management).

Crop Diversification

The decreasing share of grain crops, 74-65 % of GCA, and 77-71 % of GIA, between 1980 and 2000, shows that Indian agriculture is diversifying to cater to the increasing internal and global demand for non-grain crop products. Interestingly, perhaps as a response to the declining dominance of grains in the diet and also prices, the total grain harvested area also declined during the last two decades (Table 2). The only exception here is the area under maize, which has in fact increased due to rapidly increasing demand of livestock feed.

Among high-value non-grain crops, the area under fruits, vegetables, and roots and tubers experienced increasing growth rates over the last two decades (Table 2). It is most likely that this agricultural diversification trend will continue with the projected shift of consumption patterns. Given the recent trends, Amarasinghe et al. 2007a projects that harvested grain area

Table 2. Crop area, irrigated area and livestock population growth.

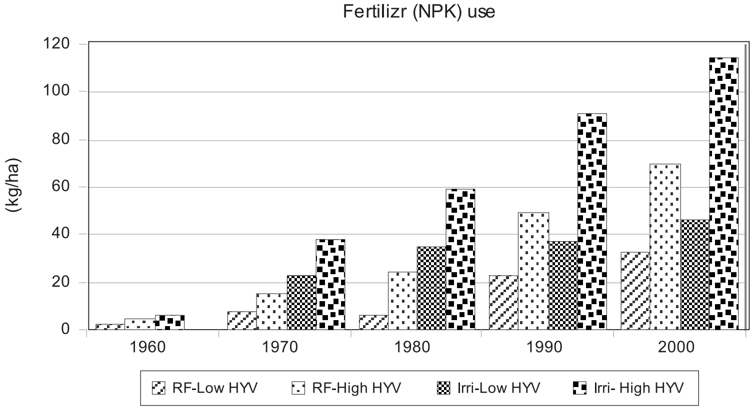
Crop or livestock item	Crop harvested area (mha)			Annual growth (%)		Crop irrigated area (mha)			Annual growth (%)	
	1980	1990	2000	1980-1990	1990-2000	1980	1990	2000	1980-1990	1990-2000
Grain crops										
Rice	40	43	45	0.6	0.5	17	19	25	1.5	2.4
Wheat	22	24	27	0.7	1.2	16	19	23	2.0	2.0
Maize	6	6	7	0.0	1.0	1.2	1.2	1.4	0.2	1.7
Other cereals	36	30	23	-1.8	-2.5	2.2	2.3	1.5	0.5	-4.3
Total cereals	104	102	101	-0.2	-0.1	36	42	51	1.6	1.9
Pulses	23	24	22	0.4	-1.0	2	2	3	2.0	1.8
Total grains	127	126	123	-0.1	-0.2	38	45	54	1.7	1.9
Non grain crops										
Oil crops	27	33	34	2.2	0.4	3	6	6	6.7	0.4
Roots and tubers	1	1	2	0.3	2.3	0	0	1	2.9	3.3
Vegetables	4	5	6	1.1	1.5	1	1	2	3.6	2.5
Fruits	2	3	4	1.6	3.4	0	1	1	4.2	4.5
Sugar	3	3	4	2.3	1.9	2	3	4	3.2	3.5
Cotton	8	8	9	-0.5	1.5	6	7	9	0.5	2.8
Livestock population (millions)										
Cows	187	203	193	0.8	-0.5					
Buffaloes	66	81	93	2.0	1.5					
Goats/sheep/pigs	141	174	195	2.1	1.1					
Chickens	0.2	0.3	0.4	4.6	2.1					

Source: FAOSTAT Database (FAO 2005)

will decrease further and consist of only 57 % of the total crop area by 2050, compared with 69 % of the NCIWRD projection. These trends project a slight increase (10 million ha) in irrigated grain area, compared with 44 million ha increase projected under the NCIWRD scenario. Thus, the irrigated grain area as a percentage of GIA based on the recent trends will be only 52 % in 2050 compared with 70 % in the NCIWRD projections. However, with the recent volatility in global grain markets and what appears to be long term increases in grain prices, these trends could change.

The projections based on recent trends show that a major part (77 %) of the additional irrigated area in the future will produce non-grain crops (Amarasinghe et al. 2007b). These are generally high-value crops, requiring timely application of expensive inputs. Although no data are available to illustrate the trends in the non-grain sector, we hypothesize that the efficacy of high value inputs very much depends on a reliable water supply during the critical periods of crop growth. This is clearly evident in the input use in the grain sector (Figure 4).

Figure 4. Fertilizer use in different land-use patterns in India.



A critical input for higher productivity, fertilizer use in irrigated areas with high-yielding varieties is much higher than in irrigated areas growing traditional varieties. Similar differences in fertilizer application exist in rain-fed areas with the use of high-yielding and traditional varieties. Indeed, a reliable water supply is a critical prerequisite for many of the other expensive inputs required for high value crop production. Groundwater, with its generally more reliable water supplies, has been a major source for meeting this irrigation demand in the recent past. But falling groundwater tables, and increasingly unreliable electricity supply and emerging energy crisis threaten this advantage and may have a significant impact on further crop diversification. How India will overcome these constraints will determine the pace of non-grain crop expansion in the future.

Irrigation Efficiency

The available information on irrigation efficiency improvement is very scanty, but that which is available suggests that the surface project irrigation efficiency has not increased much over the last decade. Although the project irrigation efficiency may be low, in water scarce river basins that are approaching a high degree of closure, the overall basin efficiency is generally much higher, that is the water lost from one project is used as supply by a project downstream. In such basins, increasing efficiency would only benefit downstream users, as has been observed in the Krishna (Venot et al. 2007). Thus, increasing surface project irrigation efficiency to the level suggested by the NCIWRD projections, i.e., 60 % will have limited effect on total water savings within these drier basins. Thus, it is important to know more about the interaction between surface and groundwater irrigation to make firm statements on utilizing water more effectively.

That said, recent studies suggest that the project efficiency of many groundwater systems is already higher than the 70 % projected by the commission for 2050. This is especially true in areas where micro-irrigation is in use, formal or informal water markets are functioning, and free electricity is not available for uncontrolled pumping. The estimates of the extent of uptake of the above interventions in different regions vary. Further research is needed to identify areas where such interventions can be practically implemented and the benefits of interventions exceed the cost.

Self-sufficiency in Grains

Can national self-sufficiency goals in food grains be a realistic assumption any more for projecting India's irrigation demand? This was so when the agricultural output in general, and grain production in particular, was a major part of the gross domestic product (GDP). The contribution of the agricultural sector to the GDP decreased from 46-25 % during 1961-2000, and will decrease further with rapidly growing services and industrial sector outputs. Moreover, the value of grain production, in comparison with total agricultural production is very small now, and is also declining, and demand for food grains is declining too. Thus, in purely economic terms, although it was a constraint for the Indian economy to import part of the grain demand now, it will be insignificant for a trillion dollar economy in a few years from now.

However, the recent volatility in the global grain markets, partly induced by significant production shortfalls in grain exporting countries and aggressive plans for developing bio-fuels, has significantly affected the price and supply of grains in a number of countries, including India. In the future, large importations of grain from populous countries like India and China could further add to the volatility. The increased costs for imports could hurt the very consumers that the imports are expected to help. In India, the major grain production deficit in the future will be for feed grains, especially for maize (Amarasinghe et al. 2007b). However, production surpluses of rice and wheat are expected to offset the production deficits of maize. Thus, in spite of price increase concerns, India's food trade will increase, and self-sufficiency of all grains need not be a rigid formula (more on this subject is discussed by R.P.S. Malik in Paper 9).

Agriculture Dependent Livelihoods

The high dependency of rural livelihoods on agriculture was a further component of the overall rationale for the commission's projections for future irrigation demand. The recent trends suggest that the agriculture demography is fast changing with increasing non-agricultural employment. Although it is not expected to see the general depopulation of all rural areas in India, as has happened in parts of South-East Asia, there are already indications that this is happening in parts of rural India. Over the last four decades, the agriculture depended population has decreased from 86-74 %. A quadratic extrapolation of the present trends (R^2=98 %) show this percentage will decline to about 58 % by 2025 and 40 % by 2050. This projected trend is more or less compatible with the present agricultural population of countries with similar economic conditions as projected for India by 2050. This means that although agriculture dependent population will increase in the short-term, it will start to decline after the next decade. And in 50 years from now, India will even have a less populace who depend on agriculture than they do now.

In fact, trends of rural population moving out of agriculture is already happening and will likely accelerate in the future with increasing employment opportunities in the non-agriculture sector (Sharma et al. 2006). There is a high probability that young rural farmers will move out of agriculture for various reasons particularly where non-agriculture employment opportunities are accessible, and the youth have better skills and education. Certainly, these conditions are increasingly apparent in many areas as urban centers continue to expand with booming industrial and service sectors.

Implications on Irrigation Demand

The above discussion shows that the key determinants of irrigation water demand of the NCIWRD projections, upon which the requirements for the NRLP have been based, are no longer consistent with the present-day trends. The NCIWRD assumed,

- increasing demand for food grains, whereas while the demand for food grains will continue to increase in the short term it will be at a declining rate, and the more significant actual trend is the increasing demand for non-food grain products;
- the grain production to dominate the future of Indian agriculture, whereas crop diversification is the actual and expected trend;
- the surface irrigation to dominate the land-use patterns, yet groundwater has been the engine of irrigation growth, and is expected to continue to be so, despite localized constraints of sustainability;
- a rather low crop yield growth, although substantial scope exists for yield improvements in both irrigated and rain-fed areas; and
- a high level of surface project irrigation efficiency, although many river basins rely on the recharge from surface return flows for groundwater irrigation and surface irrigation downstream and in these systems, surface irrigation efficiency is still as low as 30-35 %.

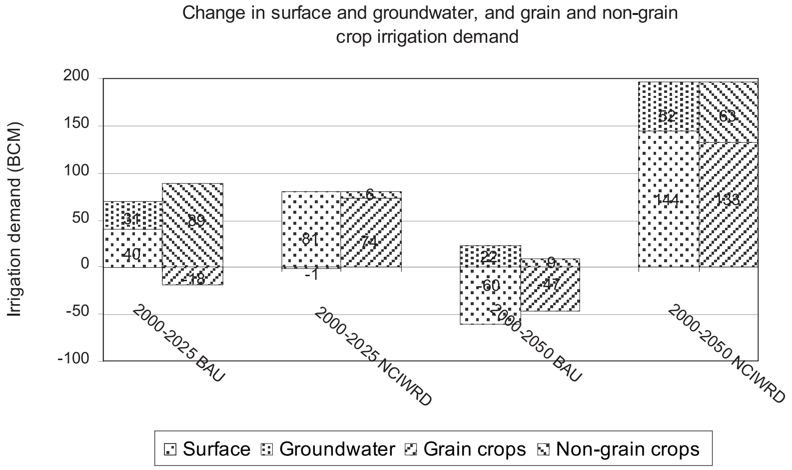
On the other hand, the recent trends suggest:

- consumption patterns will shift towards a non-food grain product dominated diet;
- agriculture will continue to expand, but it will diversify to meet the increasing demand for non food grain crops and animal products;
- groundwater irrigation will continue to expand in spite of the severe depletions in some regions;
- advanced irrigation and other water-saving technologies will spread to increase crop yields and water-use efficiency;
- better water and nutrient management will reverse the recent decline in the rate of crop yield increases, to some extent; and
- self-sufficiency in all grain crops will no longer be a concrete goal, and the production surpluses of some crops will pay for the production deficits of other crops.

Thus, irrigation water demand according to the Business as Usual (BaU) scenario trends, which is mostly based on the recent changes in key drivers as discussed above (Amarasinghe et al. 2007b), differs in many key aspects from the irrigation water demand projections of the NCIWRD report (Fgure 5).

- The BaU scenario results in a slightly lower additional irrigation demand (by about 10 billion m^3) between 2000 and 2025, and a much lower additional irrigation demand

Figure 5. Change in surface and groundwater irrigation demand and grain and non-grain in crop irrigation demand.



between 2025 and 2050. In fact, between 2025 and 2050, the irrigation demand under the BaU scenario is 38 billion m^3 less than previously predicted.

- Groundwater contributes to 44 % of BaU scenario additional irrigation demand between 2000 and 2025. And, between 2025 and 2050, the BaU scenario groundwater irrigation demand increases although the overall demand decreases. In contrast, surface irrigation dominates the NCIWRD additional water demand in both periods. The BaU scenario projects groundwater irrigation to increase by 31 km^3 between 2000 and 2025, while the NCIWRD projects it to decline by 1 billion m^3. Over the same period, additional surface irrigation water demand projection of NCIWRD is twice the projection of the BaU scenario. The differences of additional irrigation demand, both of surface and groundwater, of the two scenarios widen between 2025 and 2050.
- Non-grain crops consume a major part of the irrigation withdrawals under BaU scenario. In fact, the BaU projects decreasing irrigation demand for grain crops in both periods. However, grain crops consume a major part of the NCIWRD demand projections.

Conclusion

The major challenge facing the water sector in India today and over the long term is how to increase the groundwater stocks (supply enhancement) to arrest the declining groundwater tables, and how to sustain water use by minimizing uncontrolled groundwater pumping (demand management).

The most recent trends of the key drivers affecting water demand suggest that the required characteristics of water for agriculture will be significantly different in terms of quantity and source than those projected by the NCIWRD, upon which much of the proposed National River Linking Project has been based. However, it is also clear that if India continues along a business-as-usual path and follows these recent trends without timely and informed interventions it will lead to severe regional water crises.

Excessive groundwater exploitation will be a major component of the challenge to be tackled. In the medium-term, this will have major repercussion on changing cropping patterns, because groundwater is and will continue to be the main source of water for successful crop diversification. The challenges for the irrigation sector in India in the medium-term are,

- how to promote crop diversification to increase the benefits for every drop of consumptive water use, and
- how to promote sustainable groundwater expansion to reap the benefits of changing cropping patterns.

While it is clear from the above that the water requirements of the agricultural sector of the future will be quite different from those underpinning the NRLP as presently conceived, India does need to further develop its water resources to meet the needs of the people and the economy. Conditions will dictate that this will include large scale developments that incorporate intra - or inter-basin water transfers with surface storage. This is particularly true where increasing domestic and industrial water requirements are the dominant water consumptive factors in a relatively dry basin, and also other factors such as increasing crop diversification to high-value crops which will require a more reliable water supply and areas with declining groundwater tables which may demand better surface water supply for sustainable production and profits.

Also, there are likely to be other contingencies under which large scale inter-basin water transfers as envisioned under the NRLP are required for meeting India's future water demand. The foremost among the contingencies is that the economic growth is even more rapid than that assumed here. In such a case the domestic and industrial sector demand will be greater and will have the capacity to pay for a good quality and reliable surface water supply for their daily water needs.

Finally, the demand for biofuels will have a significant impact on water-use patterns, especially on groundwater use and may also have a significant impact on prices. Further, the climate change could have a significant impact on overall water demand and supply in many river basins. Climate change is expected to accelerate the seasonal melting of the snow pack from the Himalayas, affect the overall volume of precipitation and increase the frequency and magnitude of extreme rainfall events, which all may require large storage facilities for water use in the dry seasons (Sharma and McCornick 2006). Further research is necessary to assess the implications of these on future surface water demand.

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India’s Water Demand Scenarios to 2025 and 2050: A Fresh Look

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Introduction

India is a vast country and its water supply varies significantly across regions and river basins. Water is plenty in the northeast (Brahmaputhra and Meghna basins), but few people live there, and land availability and food production is low. In the northwest most of the water resources are diverted for crop production to the extent that this region supplies food to the deficit regions of the country making it the largest provider of virtual water, that is water embedded in food, in the county (Amarasinghe et al. 2005). Water is scarce in the south and west of the country as the naturally drier areas come under increasing demand, and the aquifers have low storage capacity.

Much of the runoff in the peninsular river basins is from the highly variable monsoon, which means it occurs during the 2 to 3 months of monsoonal rains. Thus, the regional water availability vis-à-vis changing water demand patterns and the determinants of these changing growth patterns are particularly important factors for medium to long-term water investment strategies in general in India, and in particular in the water-scarce peninsular river basins.

This report examines the implications of future water supply demand of India under business as usual (BaU) scenario trends of key water demand drivers and also under possible divergences. The assumptions of the growth of key drivers in the BaU scenario (Annex 1) in this paper significantly differ from the assumptions of the scenarios of the NCIWRD (discussed in detail in Paper 2). The BaU scenario considers the year 2000 data as the base year and the trends in the 1990s for its demand projections whereas the NCIWRD scenarios considered 1993/94 data for the base year and the trends in 1980s for determining the key drivers. This report, which is primarily, based on the studies by Amarasinghe et al. 2007a and 2007b,

- gives an overview of the business as usual (BaU) scenario food and water demand up to 2025/2050 in India;
- discusses the past trends of key determinants or ‘drivers’ of water and food demand; and

- assesses the deviations of BaU scenario projection with respect to possible deviations of the assumptions of key drivers.

The projections of food and water demand of different scenarios use the methodology of the PODIUMSIM model. The PODIUMSIM model is a tool for simulating the alternative scenarios of water futures with respect to the variation of food and water demand drivers (www.iwmi.cgiar.org/tools/PDF/PODIUMSIM.pdf).

The report is organized into three sections. It first presents an overview of the BaU scenario water demand, which is followed by a discussion of the deviation of BaU water and food demand projections with respect to the assumptions of key drivers. The final section considers development issues, which have significant investment implications for meeting India's future water demand.

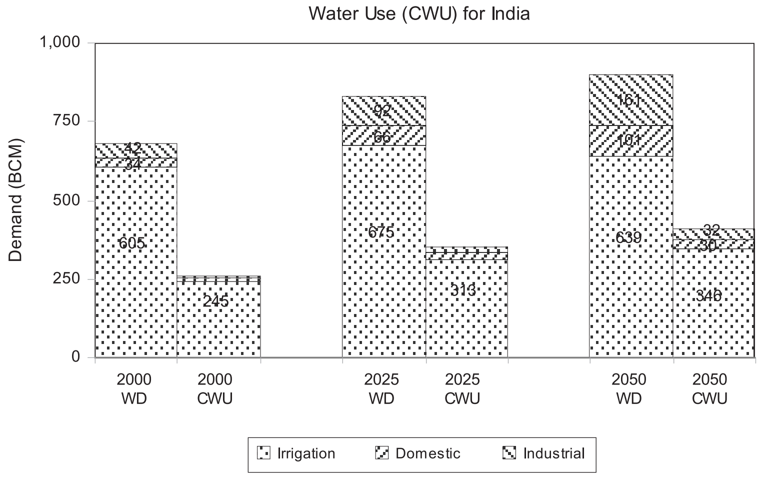
BaU Scenario – Overview

Total Water Demand

India's water demand patterns are fast changing. The water withdrawal for the agriculture, domestic use and industry, the three most consumptive water use sectors, in 1960 was 277 billion cubic meters (bcm) (Shiklomanov 1999). This has since increased to about 680 bcm in 2000. The BaU scenario, based on the PODIUMSIM analysis, projects that the total water demand will increase by another 150 bcm, or 22 % by 2025; and a further 69 bcm or 8 % by 2050 (Amarasinghe et al. 2007a) (Annex 1 for details of the assumptions on key drivers and comparison with other different scenarios of water demand projections).

However, the dominance of agriculture in the water demand is projected to change over time (Figure 1). Although agriculture is still the largest water use sector, the share of it in the

Figure 1. Water demand and consumptive water use of the agriculture, domestic and industrial sector of India.



total water demand is expected to decrease. Irrigation has accounted for 98 % of the total withdrawals in 1950, and 89 % in 2000. BaU trends projects a further decline – 81 % in 2025, and 71 % in 2050. However, the irrigation demand will increase in absolute terms between 2000 and 2025, and will decrease between 2025 and 2050. The decrease in demand during 2025 to 2050 is due to various factors including expansion of groundwater use, spread of micro irrigation technologies, higher irrigation efficiencies and decreased demand for grain crop, especially rice.

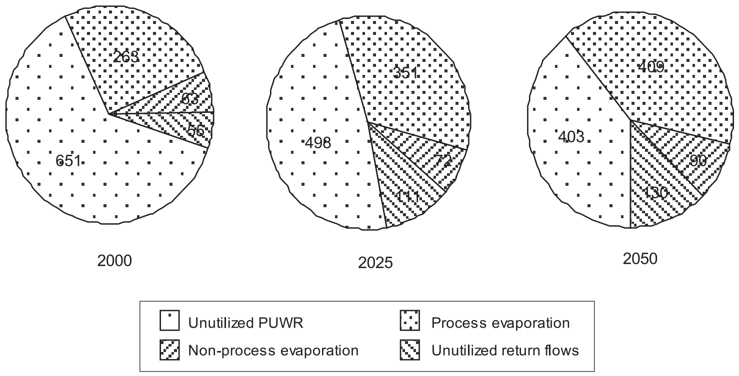
The domestic and industrial sector water demands, unlike in the agriculture sector, are increasing rapidly. The shares of the domestic and industrial sectors of the total water withdrawals are projected to increase, from 5 and 6 %, respectively in 2000, to 8 % and 11 % by 2025, and 11 % and 18 % by 2050 (Figure 1). Rapid growth of the industries and services, which is associated with recent economic expansion and urbanization are the major causes for this increasing demand. In fact, unlike in the past, the total additional water demand of the domestic and industrial sectors is projected to exceed the additional irrigation demand, and accounts for 54 % growth between 2000 and 2025, and 85 % of growth between 2025 and 2050.

Water Accounting

In spite of the large water withdrawals, India has very low consumptive water use or process depletion. The process depletions, the water depleted through evaporation and transpiration in the process for which the water is diverted, was only 39 % of the total withdrawals in 2000 (authors’ estimates based on PODIUMSIM model). In irrigation, the average process evaporation at the project level is estimated as only 41 %. However, all the water lost at the project scale, is not lost at the basin scale. The return flows to surface and groundwater systems in one location are again reused in downstream locations. This results in basin water use efficiency being higher than the system efficiency.

Figure 2 shows the aggregate water accounting at the national level. The water accounting of the BaU scenario, estimated according to Molden’s water accounting framework (Molden 1997), was assessed at the river basin level. The process depletion from all basins in 2000 was 69 % of the primary water withdrawals, but was only 39 % of the total water withdrawals. This indicates that much of the return flows of the primary water withdrawals are reused as surface or groundwater downstream. The primary water withdrawals as a percentage

Figure 2. Water accounting of potentially utilizable water resources (in billion cubic meters) of all river basins in India.

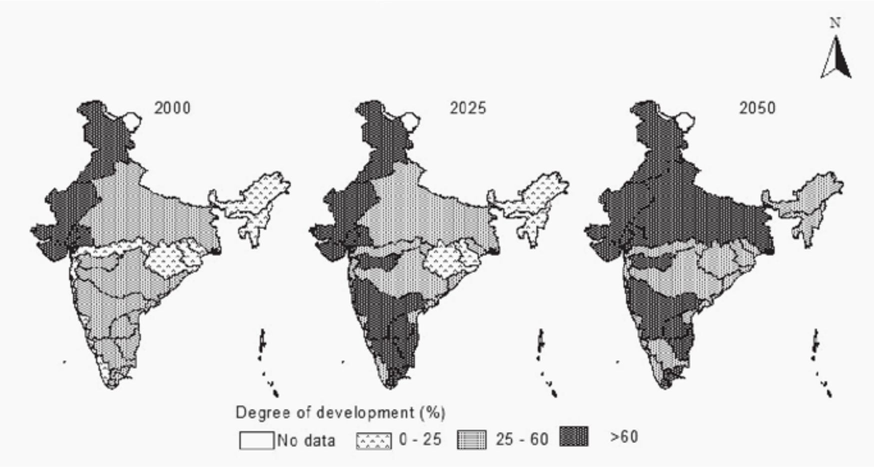


of potentially utilizable water resources, called the *degree of development*, in 2000 was only 37 % (authors' estimates based on PODIUMSIM model). This ratio is estimated to increase to 52 % and 61 % by 2025 and 2050, respectively (Amarasinghe et al. 2007b). When the degree of development exceeds 60 %, the basins or countries are classified as physically water-scarce (Seckler et al. 1998; IWMI 2000). High physical water scarcity indicates severe physical and economic constraints for further development of the water resources. In physically water-scarce river basins, there are not enough utilizable water resources left for further development without affecting the environment and the other riverine water users. It also indicates progressively high cost of developing the remaining water resources.

Although the degree of development at the national level and also of few relatively large river basins are low at present, several other river basins are already physically water-scarce due to water supply and demand mismatches (Figure 3). In other words, they have a high degree of development. This situation is expected to worsen in the future. Four basins, the Indus, Sabramati, Mahi and west flowing rivers of Kutch and Saurashtra, with 11 % of the total population, were physically water- scarce in 2000. A further 11 basins are projected to reach this status by 2050, and as a result three-quarters of the total population will live in such basins.

Many basins will require substantial additional water resources to meet the future demand by 2025. These basins are economically water-scarce where the additional water requirements by 2025 exceed 25 % of the primary water withdrawals at the 2000 level. The economic water-scarce basins require substantial investments if these additional water demands are to be met.

Figure 3. Degree of development of Indian river basins.

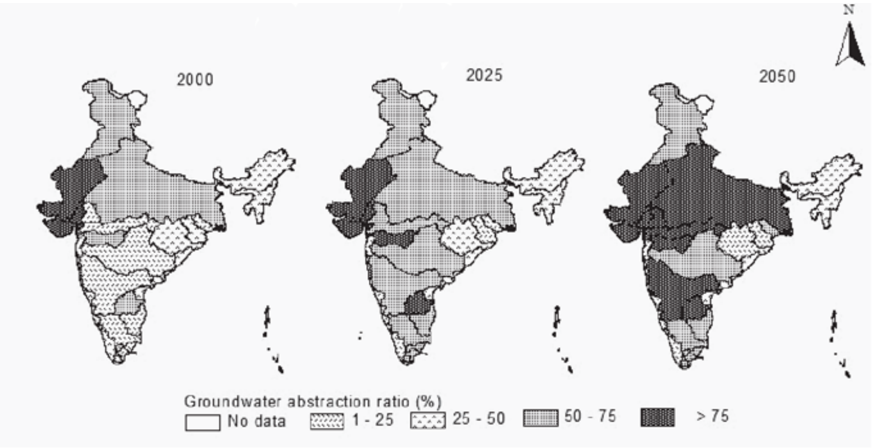


Groundwater Use

Groundwater development was the main driver of irrigation expansion in the 1980s and 1990s. This reliance of groundwater is projected to continue further. India abstracted about 300 bcm of groundwater in 2000 of which 91 % was for the agriculture sector (authors' estimates based on PODIUMSIM model). Amarasinghe et al. 2007b projects that total groundwater withdrawal will further increase, 11 % by 2025, and 7 % more by 2050.

As the reliance of groundwater, especially for irrigation, increases, many basins will have severe groundwater depletion. According to the BaU scenario, many basins will have groundwater abstraction more than 75 % of their utilizable groundwater resources by 2050. Figure 4 shows the groundwater abstraction ratio - the ratio between total groundwater withdrawals and the total utilizable groundwater resources. The utilizable groundwater resource is defined as the available groundwater through natural recharge from rainfall and the artificial recharge from the return flows of various uses. As the water use patterns are not uniform within basins, many regions of these basins will have unsustainable water use patterns, and even economically profitable cropping patterns may become hydrologically unsustainable (e.g., rice-wheat in the western IG basin).

Figure 4. Groundwater abstraction ratio of Indian river basins.



Crop Production Surplus or Deficits

We also present the production surplus or deficit estimates, the difference between the production and consumption demand of major crop or crop categories resulting under the BaU scenario water use patterns. The consumption demand estimates here are based on the food consumption demand estimates of the rural and urban population and the feed demand for the livestock sector at the state level (Amarasinghe et al. 2007b). The food production estimates are based on the cropping patterns and crop productivity growth assumptions at the state and district level (Amarasinghe et al. 2007a). Despite the complicating water picture described above, India has substantial rice and wheat surpluses in 2000 and will continue to be so in the future. Past trends show per capita consumption of rice in both the rural and urban areas are decreasing and consumption of wheat is stabilizing. With these changing consumption patterns and with rather optimistic crop productivity growth assumptions, BaU scenario projects production surpluses for rice and wheat to increase substantially by 2025 and even more by 2050 (Table 1). However, the present production deficits for other cereals (maize and other coarse cereals) are projected to get significantly worse over the same time frame primarily due to rapidly increasing maize demand for livestock feeding. The maize demand is projected to increase from 5 mmt in 2000, to 107 mmt by 2050. However, the production

Table 1. Production, demand and production surpluses or deficits of different crops.

Crop	Production			Demand			Production surpluses/ deficits as % of demand		
	2000	2025	2050	2000	2025	2050	2000	2025	2050
	mmt	mmt	mmt	mmt	mmt	mmt	%	%	%
Rice	89	117	143	82	109	117	8	7	22
Wheat	72	108	145	67	91	102	8	18	41
Other cereals	32	49	78	37	73	137	-16	-33	-43
Pulses	13	18	19	14	18	21	-5	-3	-7
Total- Grains	207	292	385	201	291	377	3	1	2
Oil crops	31	73	97	48	103	133	-35	-30	-27
Roots/tubers	7	14	26	7	13	24	-3	10	7
Vegetables	74	150	227	75	150	189	-1	0	20
Fruits	46	83	106	47	78	123	-1	6	-14
Sugar	30	46	60	26	42	55	14	9	10
Cotton	2	4	6	2	4	6	-12	-2	-3
Grains (BUS$)[1]	54	74	93	52	73	90	3	0.4	3
Non-grains (BUS$)[1]	96	187	266	106	198	284	-9	-5	-6
Total (BUS$)[1]	150	261	359	158	272	374	-5	-4	-4

Sources: 2000 data are from the FAOSTAT database (FAO 2005); the 2025 and 2050 data estimated from the PODIUMSIM analysis (Amarasinghe et al. 2006) author.

Note: [1] The value is in billion US$ and is expressed in terms of average of the export prices in 1999, 2000 and 2001.

surpluses of rice and wheat offset the deficits of other cereal crops to maintain overall grain production surpluses by 2050.

Among the non-grain crops, oil crops and fruits will have substantial production deficits by 2050. Fruits record a production deficit by 2050, where increasing demand will far outweigh the production. However, this situation may change if the conversion of wastelands to orchards will significantly increase. The total production of non-grain crops, estimated in terms of the average export prices of 1999-2001, was 9.4 % less than the non-grain crop demand in 2000. However, with increasing sophistication of the market demand and resulting crop diversification, this deficit is projected to decrease to 6 % by 2050. The total value of the production of all crops is projected to have a slight deficit, about 4.0 % by 2025 and 2050.

Key Determinants of Water Demand - Sensitivity

Trends in the 1990s were used as a guide for determining the future growth of the key drivers of BaU. However, slight changes in many of these key drivers will have significant changes in the demand projections. Here, we highlight three drivers which could have a significant bearing on the water demand and also for decisions on future investments in the water sector.

Groundwater Irrigation Growth

Until mid-1980s, surface irrigation was the major source of irrigation in Indian Agriculture, and the groundwater development was considered to have been within the canal commands. But, since mid 1980s, groundwater is the major source of irrigation for many regions and districts, and in some cases spreading to areas even outside the canal commands (Bhaduri et al. in this volume, Shah et al. 2001). In fact, groundwater irrigation has contributed to virtually all of the net irrigated area (NIA) growth since mid 1980s. BaU scenario projects this trend to continue, and assumes that

- the on-going major to medium irrigation projects will also add another 10 million ha (mha) of net surface irrigated area (NSIA) by 2025, and growth of NIA after 2025 is primarily groundwater driven; but
- the groundwater irrigated area expansion will slow down due to excessive depletion in some basins and net groundwater irrigated area (NGWIA) is assumed to increase from 37 mha in 2000 to 50 mha by 2050; and
- as a result, the gross irrigated area increases from 77 Mha in 2000 to 117 Mha by 2050.

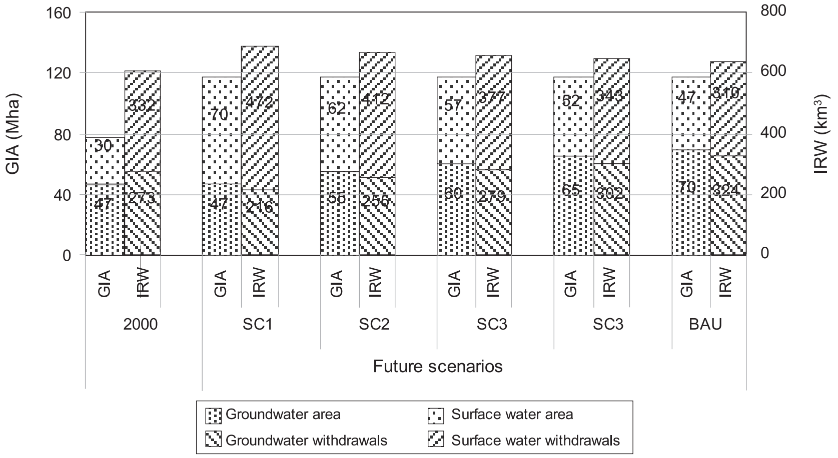
But, the crucial question is how far can groundwater irrigation expand in India beyond the 2000 level? If NGWIA increases to 50 Mha (as assumed in the BaU scenario), because of the increased cropping intensity the gross groundwater irrigated area (GGWIA) is estimated to increases to about 70 Mha. But according to the Central Ground Water Board the estimated gross groundwater irrigation potential stands at only 65 Mha, and according to Sanghal (1987) the groundwater coverage is estimated as 80 Mha. A recent study (Thenkabail et al. 2006), using remote sense imageries, estimates that NIA of India is already 100 Mha, in contrast with the 56 Mha reported by official statistics. The same study also determined that a greater portion of the irrigated area is supplied by groundwater, and the gross irrigated area is close to 133 Mha. So, the assumption on the growth of groundwater irrigation still could deviate substantially than that assumed under BaU scenario.

First, we assess the implications of these deviations on the total irrigation demand using four alternative scenarios (SC1-SC4) of slower growth of the groundwater irrigated area (Figure 5). SC1 relates to no further expansion of the ground water irrigated area from the level of 2000 and SC2, SC3 and SC4 relate to the increase of gross groundwater irrigated area to 55 Mha, 60 Mha or 65 Mha, respectively. In each case, we assumed gross irrigated area (117 Mha) and the efficiencies of surface water and groundwater irrigation remain the same.

Deviations SC1 and SC2 from the BaU scenario require substantial increases in withdrawals of surface water (140 km^3 under SC1 and 80 km^3 under SC2), but lower withdrawals of groundwater (57 km^3 under 18 km^3 under SC2) from the 2000 level (Overall water requirement under SC1 and SC2 will increase by 14 % and 10 %, respectively. While such growth in irrigation scenarios can be a big relief for over exploited groundwater basins, it requires substantial investments in surface water development for meeting the projected food demand.

On the other hand, deviations SC3 and SC4 from the BaU scenario would result in an increase in both surface and groundwater irrigation withdrawals (43 km^3 and 6 km^3 in SC3 and 11 km^3 and 29 km^3 in SC4, respectively) from the 2000 level. These two scenarios, while still

Figure 5. Gross irrigated area (GIA) and irrigation withdrawals (IRW).



Source: Authors' estimates using PODIUMSIM

require developing more surface water resources will also increase the pressure on already overexploited groundwater resources in water-scarce basins.

What are the implications of keeping the groundwater irrigation withdrawals at the level of abstraction in 2000? With the projected irrigation efficiencies in the BaU scenario, the groundwater irrigated area can then be increased by another 12 Mha from the 2000 level. This requires doubling the gross surface irrigated area to 58 Mha, and increasing surface irrigation withdrawals by 54 km^3 to meet the projected crop production under the BaU scenario.

The above analysis shows that deviations in the form of slower growth of groundwater irrigation than assumed in the BaU scenario would require substantial investments in developing surface water resources. However, if only the groundwater irrigation potential projected by the Central Groundwater Board is used in irrigation, then India would be using only two-thirds of its available groundwater resources. However, even under this scenario, many river basins will still have severe regional overexploitation.

It is important to note that all these scenarios assumed a reasonable increase in the efficiency of both groundwater and surface water use for irrigation. We assess the implication of deviations from assumed efficiencies next.

Growth in Irrigation Efficiency

The BaU scenario assumes a modest growth of surface and groundwater project efficiency. First, from the information available, the project efficiency of surface irrigation systems has not improved much over the years. But it is clear, however, that the nonagricultural sector water demand, especially for surface water, is increasing at a faster rate, and the irrigated agriculture will have to produce more with less water. So, it is imperative that project surface irrigation efficiency increases, from the present level of about 30-40 %, to meet this growing demand. That said, in some basins, increasing the project efficiency in certain systems will negatively affect other water users downstream. The return flows of many low efficiency surface irrigation systems are either a source for more productive groundwater agriculture or to meet the environmental water needs in the downstream. As discussed earlier, the overall efficiency of these basins, where return flows are recycled and reused, is already high. Thus, increasing surface efficiency for that saved water to be consumed by other upstream users could only adversely affect the downstream water users. The BaU scenario assumes that surface project irrigation efficiency increase to about 45 % by 2025, and 50 % by 2050. Clearly such efforts should be targeted at locations where both the project and the basin level efficiencies are relatively low, and careful consideration needs to be given as to how to improve the management of these schemes that are at stubbornly low levels to date.

Second, the water saving technologies and the institutional interventions for increasing the efficiency of groundwater are spreading. Decreasing public investments in major and medium irrigation, food and livelihood security for the agriculture dependent rural households coupled with low energy prices and free electricity supply have contributed to the recent groundwater boom. As a result, the depth to the groundwater table in many locations is increasing at an alarming rate, and the physical or the economic water scarcities are emerging in many locations. At the same time, the energy prices are escalating, and providing free electricity for the agriculture sector is becoming a huge burden to the state coffers, and the solvency of the power companies. Using diesel for pumping long hours is not a viable proposition any more for the small and marginal farmers. Innovations such as informal water markets, regulating electricity supply to agriculture through separate power lines, and water saving technologies are being promoted to address the problems in the groundwater irrigated agriculture. All these measures have been shown to increase the water use efficiency. For example, drip and sprinkler irrigation are generally 15-20 % more efficient than the flood irrigation. The BaU scenario assumes that this trend towards higher efficiency technologies will continue, and the overall groundwater efficiency would increase from about 65 % in 2000 to 75 % by 2050.

However, with increasing scarcity and escalating energy prices, farmers may increasingly opt for micro-irrigation techniques, such as sprinklers and drip, for enhancing water use efficiency. Efficiency of a well managed sprinkler and drip system can be as high as 80-95 % (Narayanmoorthy 2007). If the overall groundwater irrigation efficiency can be increased to 80 %, 5 % over the BaU scenario, the total irrigation water demand in 2050 could go down by 32 BCM; and with 5 % more groundwater irrigation efficiency growth, the total irrigation demand could decrease another 20 BCM. This reduction in groundwater pumping could reduce the over abstraction to a great extent in many water-scarce basins, although the actual consumption of water would remain the same as projected under the BaU.

Crop Productivity Growth

Until now, India’s growth in crop yields has been stubbornly low in comparison with that of other countries with major irrigated agriculture sector. For example, grain crops always had a preeminent position in Indian agriculture, and, as a result, the country is one of the three largest grain producers in the world today. But India also has one of the lowest yield growth among all grain producers. Between 1960 and 2000, average grain yields increased only by 1.0 ton/ha in India, from 0.7 tonnes/ha in 1961, while China increased its grain yields by 3 tonnes over the same time period; and the USA increased its yield by almost 4 tonnes/ha. Compounding the low yields, the rate of growth also has been decreasing in the last decade, from an all time high of 3.8 % annually for grains in the 1980s to 2.0 % in the 1990s. Recent policy decisions of the government of India suggest that there will be more investments for research and development for increasing crop productivity in the coming decades. Therefore, although the BaU scenario does not anticipate a complete reversal of the declining trends of crop productivity, it expects a reduction in the rate of decline of the growth rates. In fact, this rather optimistic assumption of growth in crop yield is a key component of BaU scenario food and water demand projections.

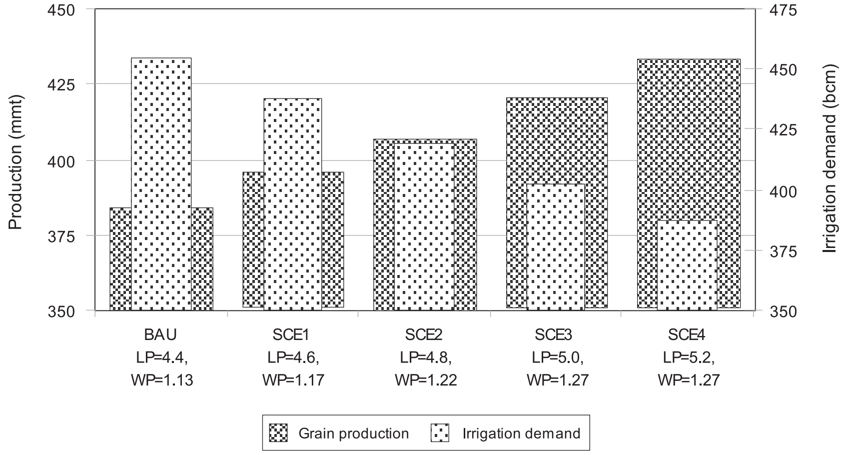
In spite of these decreasing trends, this analysis assumes that a substantial scope exists for increasing the yield beyond the current level. A significant gap exists in many locations between the highest and the lowest actual yields, and between the actual and the potential yields. The future investments, both private and public sector, focus on small-scale infrastructure and technologies that enhance the crop yields. Breeding of rice hybrids and improved varieties of other crops (improving harvest index), reducing losses through pests and diseases and post-harvest losses, expanding groundwater use and micro irrigation technologies offer significant opportunities for the irrigated yield growth. And the supplementary irrigation, through water harvesting (Sharma et al. in this volume), at critical periods of water stress, can substantially boost rain-fed yields. Moreover, farmers will have an incentive to increase crop productivity to benefit from the increasing internal and external food trade. Thus, the BaU scenario crop productivity growth rate assumptions are somewhat optimistic than the assumptions recent trends indicate. Even these assumptions to some extent are conservative according to some, as they argue that a second green revolution is well overdue. If that happened it could dramatically change this yield growth scenario.

BaU scenario in this paper projects the decreasing trend of yield growth to continue, albeit at a slower rate. The grain yield growth is expected to be 1.5 % annually between 2000 and 2025, and 1.0 % annually between 2025 and 2050. BaU scenario assumes a similar growth pattern for non-grain crops.

Irrigated agriculture is estimated to contribute three-quarters of the crop production by 2050. Thus, a small increase in the irrigated yield from the BaU scenario can significantly increase the crop output from the same irrigated area or reduce the irrigation demand to maintain the same production levels. For example, the BaU scenario expects the irrigated grain yield to increase from 2.6 to 4.43 tonnes/ha between 2000 and 2050. But our analysis shows that crop yield growth assumptions indeed are very sensitive to the total crop production and irrigation water demand projections. Figure 6 shows grain production and irrigation demand under different land productivity (LP in tonnes/ha) and water productivity (WP in kg/m^3 of consumptive water use) growth assumptions. SCE1-SCE4 assume that land or water productivity increase annually at 0.08 to 0.30 % higher than the assumed growth in the BaU scenario.

If irrigated land productivity can be doubled by 2050, as indicated in SCE4, then the grain production can be increased by 13 % from the same irrigated area. On the other hand, if water productivity is doubled, the crop production can be maintained at the BaU scenario level with 15 % less irrigation withdrawals. Is this a realistic goal to achieve? One could argue that, given the significant productivity variations that exist in similar agro-climatic zones (Molden et al. 1998), doubling water productivity in 50 years is not an impossible target to achieve. The SCE4 has the average grain yields of China in 2000. Can India reach the China's yield levels in 50 years from now? If it can, future grain production requires much less irrigation water than they use now.

Figure 6. Grain production and irrigation demand under different assumptions of land and water productivity growth.



Source: Authors estimates based on PODIUMSIM analysis.

Rain-fed Crop Production

Although the above discussion mostly focused on irrigation, a brief description of the potential improvements in the rain-fed agriculture is required here. Rain-fed agriculture, water harvesting and the related yield improvements are discussed in detail in two later papers. We discuss here only the rain-fed agriculture contribution to the BaU scenario. Another key assumption of the BaU scenario is that India's net sown area will remain the same in the period 2000-2050. This assumption implies that the existing rain-fed area is either replaced by the new irrigated area or taken over for the nonagricultural purposes. Over the period 2000-2050, the rain-fed crop area under the BaU scenario is projected to decrease from 60-44 % of the gross cropped area. How will then rain-fed agriculture contribute to overall crop production?

In 2000, grain area under rain-fed agriculture was 57 % of the total grain area, and contributed to 33 % of the crop production. Abysmally low rain-fed yield was the main reason for low contribution. India's grain yield, only 0.97 tonnes/ha in 2000, is one of the lowest among the countries with significant rain-fed areas. It is only 20 %, 32 % and 37 % of the rain-fed yield of the USA, China and Argentina, respectively. Given these differences, it seems that a substantial scope exists for improvements in the rain-fed yield in the future. Indeed, in Paper 10, Bharat et al. show that with proper application of inputs and a small dose of supplemental irrigation in the water stress crop periods the yields of many rain-fed crops can even double.

The BaU scenario assumes that the rain-fed yield will increase to 1.3 tonnes/ha in 2025, and 1.8 tonnes/ha by 2050. That is the BaU assumes that rain-fed yield will increase by 80 % over the 50-year period from 2000. By 2050, the rain-fed area will consist of 34 % of the total grain area, but contributes to 28 % of the total grain production. This contribution can be increased further with the higher growth in rain-fed yield. The results of that obviously is lower requirement for irrigated area expansion and hence irrigation. In Paper 10, Bharat et al. show that local water harvesting, in extremely non-arid or non-wet areas, could indeed provide the small supplemental irrigation that is required for the rain-fed yield increase. However, in Paper 14, Dinesh et al. show that water harvesting potential is very low in water- scarce areas due to physical and institutional constraints. Further research is required to identify the high potential rain-fed areas where water harvesting is feasible for providing the small supplemental irrigation.

Conclusion

This report discussed the implications of future food and water demand under the business as usual scenario trends. For most determinants, the BaU scenario assumes the growth patterns of the recent years for future projection. For the yield growth, based slightly optimistic assertion of agriculture investments, we assume somewhat higher growth rates than the recent trends.

On the water demand side the BaU scenario projects that:

- India's total water demand, for the irrigation, industrial and domestic sectors, increases 22 % and 32 %, respectively by 2025 and 2050, from the estimated withdrawals of 680 bcm in 2000;
- industrial and domestic sectors account for 54 % and 85 % of the additional water demand by 2025 and 2050, respectively;
- groundwater use will contribute to a major share of the future irrigation water withdrawals;
- and on the supply side several basins will reach physical water-scarce condition by 2050, where the remaining utilizable water supply cannot be developed further without making a severe impact on the environment and riverrine water users down stream; and
- groundwater abstraction to increase significantly and many basins will have unsustainable water use regions, where the total available groundwater through recharge from natural rainfall and return flows in some regions are not adequate for meeting the increasing demand.

The agriculture water demand projections have accounted for the expected changes in consumption patterns. The BaU projections show that on the food demand side,

- India's preeminence in food grains in the diet is changing, and food grain consumption will continue to decrease from 471 grams/person/day in 2000 to 454 and 417 grams/person/day, respectively by 2025 and 2050;
- non-grain crop products including vegetables, fruits and vegetable oil, and animal products, primarily from dairy and eggs, will provide a major part of the nutritional intake by 2050; and
- due to increasing animal product consumption, the feed grain demand will increase significantly from a mere 8 mmt in 2000 to about 38 and 111 mmt by 2025 and 2050.

And, on the food supply side,

- there will be production deficits of maize and pulses, but the production surpluses of rice and wheat offset this deficit, and will have grain production surpluses over the demand;

- oil crops and fruits will have production deficits by 2050; but
- crop diversification will help decrease the overall value of crop production deficits from 9 % of the demand in 2000 to about 4 % by 2050.

The sensitivity analysis shows that changes in the ground water irrigated area, groundwater efficiency and crop productivity could significantly alter the BaU food and water demand projections. A slight crop productivity growth, in both irrigated and rain-fed agriculture, beyond the BaU assumption could result in a significant

- reduction in water needs for meeting the projected food demands; or
- increase in food production from the projected level of BaU irrigation withdrawals.

In fact crop water productivity growth is by far the best option for meeting future food demand while reducing the pressure on water resources. It is imperative that India should invest in increasing research and extension for increasing their crop productivity from the dismal levels at present.

Groundwater expansion is also an influential driver on future water demand. Given the present investment patterns, groundwater will continue to play a major role in irrigation expansion in the short to medium terms. Groundwater expansion not only reduces the withdrawal requirement, but could also lead to higher crop productivity and economic benefits. However, overexploitation in different river basins could be a serious constraint for sustaining groundwater expansion in the future. India should invest in artificial recharge programs for increasing the groundwater stocks where opportunities exist to capture water from under developed basins or sub-basins and recharge into appropriate aquifers as long as it does not create adverse impacts in the down stream water users.

India should also introduce physical and institutional interventions including micro irrigation techniques, regulating the electricity supply and introducing efficient water markets, for reducing the uncontrolled pumping in many river basins. Depending on the extent of the success of these programs groundwater expansion will continue to expand and benefit the irrigation users.

It is also important to note that it may be inevitable that India will have to find adequate surface water resource for meeting the increasing domestic and industrial water requirements. The additional surface water resource required for these two sectors exceed the estimated surface water reallocation from the irrigation sector. This requirement may increase beyond the BaU scenario estimates with a higher growth in Indian economy.

Annex 1.

Assumption of Key Drivers in the BaU Scenario

The assessment of BaU scenario uses the methodology of PODIUMSIM model Policy Dialogue Model Simulation for projecting India's water future. The PODIUMSIM is a tool for simulating the alternative scenarios of food and water future with respect to the variation of food and water demand drivers. The model has four major components, which can assess food and water demand at various temporal and spatial scales: crop demand (annual and state/river basins/ national), crop production (seasonal and districts/state/river basins), water demand (monthly and districts/state/river basins) and water accounting (annual and river basins) (for more details see www.iwmi.org/applications/podium). Annex Table 1 gives the key drivers of the BaU scenario and few other comparable scenarios projecting India's water futures.

Changing consumption patterns is a key driver for estimating food demand in the BaU scenario. The BaU scenario projects that significant increase in contribution from non-grain food crops and animal products increase the total nutritional intake, whereas the NCIWRD scenario projects increasing dependency on food grains. According to the BaU trends, expanding groundwater irrigation and changing cropping patterns are key drivers for projecting the irrigation demand, whereas the NCIWRD scenario projects significant increases in surface irrigation of grain crops, with a substantial rice area. Changes in cropping patterns and irrigation efficiencies reduce the irrigation demand under BaU scenario between 2025 and 2050. However, due to high demand for irrigating grain crops, total irrigation demand under the NCIWRD scenario increases significantly over the same time period. Increase in domestic and industrial water demand is more than 85% of the additional water demand between 2000 and 2050 under the BaU scenario, while it is only 48 % under the NCIWRD scenario.

Seckler et al. 1998; IWMI 2000; and Rosegrant et al. 2002 scenarios only projected food and water demand to 2025. Both scenarios assumed lower population projections and higher demand for food grains than the BaU. The overall water demand projection of Rosegrant et al. scenario, after adjustment for the differences of population projects, is similar to that of BaU, while Seckler et al. 1998 scenario project higher total water demand.

Annex Table 1. Summary of the key drivers and water demand projections of BaU and other scenarios for India.

Drivers	Unit	2000[i]	BaU scenario projections[ii]		NCIWRD high demand scenario[ii]		Seckler et al.[ii]	Roasgrant et al.[ii]
			2025	2050	2025	2050	2025	2025
Population	Million	1,007	1,389	1,583	1,383	1,581	1,273	1,352
- % urban population	%	28	37	51	45	61	43	43
Total calorie supply/person/day	Kcal	2,495	2,775	3,000	-	-	2,812	-
- % of food grains	%	65	57	48	-	-	58	-
- % from non-grain food crops	%	28	33	36	-	-	32	-
- % from animal products	%	8	12	16	-	-	11	-
Food grain demand/person/year	Kg	172	166	152	210	284	188	183
Total grain demand/person/year	Kg	200	210	238	231	312	215	215
Net sown area	Mha	142	142	142	144	145	-	-
Net irrigated area	Mha	55	74	81	67[iii]	93[iii]	-	-
- from groundwater	Mha	34	43	50	34[iv]	42[iv]	-	-
Gross irrigated area	Mha	76	105	117	98	146	90	76
Irrigated area of grains	Mha	54	59	63	69	102	61	51
Rain-fed area of grains	Mha	69	62	57	70	57	61	69
Total grain availability/person/year	Kg	208	213	240	242	312	216	206
Net irrigation requirement	Km^3	245	313	346	359[iv]	536[iv]	323	332
Irrigation efficiency- surface water	%	30-45	35-50	42-60	50	60	-	-
Irrigation efficiency- groundwater	%	55-65	70	75	72	75	-	-
Total irrigation demand	Km^3	605	675	637	611	807	702	741
- from groundwater	Km^3	272	304	325	245	344	-	-
Irrigation for grain crops	Km^3	417	398	351	428	565	-	-
Domestic water demand/person	m^3/day	33	45	64	45	70	31	31
Industrial water demand/person	m^3/day	42	66	102	48	51	55	
Total water demand	Km^3	680	833	900	773	1,069	811	822

Notes:

[i] Data for 2000 is from various publications of Government of India;

[ii] BaU, NCIWRD, Seckler et al. and Rosegrant et al. Information is compiled from GOI 1999, Amarasinghe et al. 2007b, IWMI 2001, and Rosegrant et al. 2002, respectively.

[iii] Estimated with cropping intensities- 141 % in 2025 and 155 % in 2050; [iv] Estimated with percent from groundwater irrigation- 50 % in 2025 and 43.7 % in 2050.

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Meeting India's Water Future: Some Policy Options

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Introduction

The best course for managing and further developing India's water resources is a hotly debated subject, with some of the more contentious arguments centered on the large scale interbasin transfers planned as part of the National River Linking Project (NRLP). As part of a broader study to examine the NRLP and potential alternatives, this paper seeks to identify some of the more promising policy options which could be part of a strategic and holistic effort to address India's future water challenges.

Accounting for the characteristics of recent water resources development and management, the paper considers the future water needs should the country continue along this business as usual (BaU) path. In addition to the developments proposed under the NRLP, the other considered policy options , which could serve to replace or remove the need for elements of the NRLP, or which compliment elements of the NRLP, include increased emphasis on recharging groundwater to offset the over abstraction; adoption of water saving technologies for increasing water use efficiency[1]; formal or informal water markets; provision of more reliable yet rationed rural electricity supply to reduce uncontrolled groundwater abstraction; and increasing research and extension for enhancing agriculture water productivity.

As in many countries, agriculture is the largest user of water in India, and as such has and will continue to be a major driver of water resources management and development in the country. The dominance of food grains and the prominence of surface irrigation in India's agricultural production are gradually changing. In fact groundwater is already the dominant water source for agriculture, and recent trends show that agriculture is diversifying to cater to the changing domestic consumption patterns and increasing export opportunities. Groundwater irrigation is continuing to expand to meet the increasing demand of water in agriculture. Generally the agricultural diversification is to higher value crops and livestock, which in most cases requires costlier inputs, and necessitates a relatively reliable water supply. Until now, the inherent reliability of groundwater has made it the source of choice.

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[1] However, in many cases while such technologies may reduce the amount of water pumped, it may not result in water savings at the basin scale.

The unplanned development of the resource, and the difficulties of managing it thereafter means that an increasing number of aquifers are over exploited, resulting in high social and environmental cost, and jeopardizing the reliability of the supply. Groundwater resources within many river basins will soon reach this critical stage with continuing groundwater expansion (Amarasinghe et al. 2007). Without appropriate management strategies and interventions, these unsustainable practices will lead to serious crises, perhaps in the near future and most certainly within the next four to five decades for some regions. We discuss the pending water crisis in the next section.

However, there are a number of policy options which could avert such a crisis. Artificial groundwater recharge, increasing efficiency of groundwater use, reducing uncontrolled groundwater pumping can sustain the groundwater expansion. Among others, increasing productivity and diversifying with proper cropping patterns can also offer a significant leverage. We discuss these policy options in detail in the third section.

In spite of these options, there are situations where major interbasin transfers may still be inevitable, especially over the long term. The justification and necessary support for such investments is unlikely to come from the development of new irrigated areas, at least not as a significant part of the investments, but is more likely from a combination of increased domestic and industrial water demand, providing a reliable water supply for high-value crops, growing pressure on the groundwater systems, escalating energy prices, and from increased efforts to account for environmental needs. We discuss them in the final section.

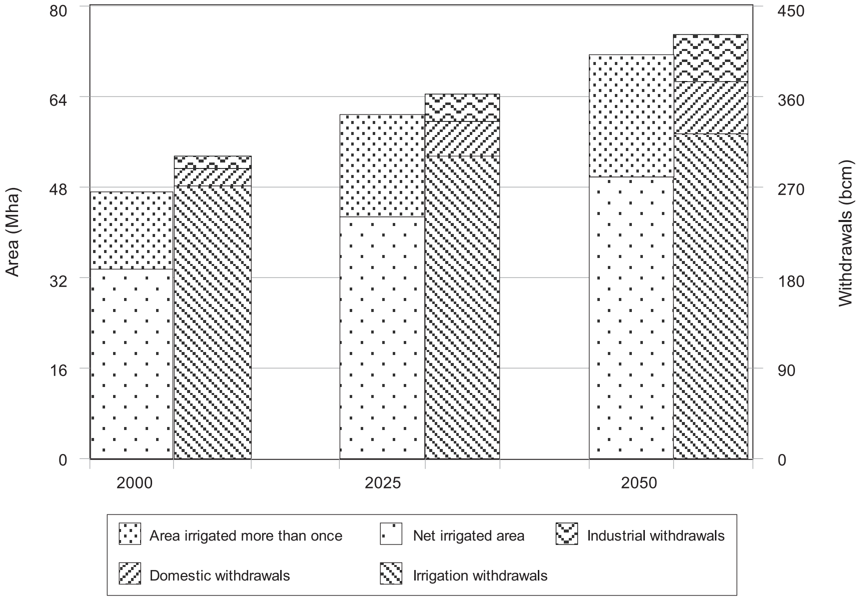
Pending Water Crisis

India already withdraws about 273 cubic kilometer (km^3) of groundwater per annum, which is estimated to be around 60 % of the sustainable yield (Amarasinghe et al. 2007). Given that most of the groundwater is abstracted for agriculture and that most has been developed by the private sector, it is anticipated that groundwater will continue to be the major source for future growth in irrigated areas.

Projections based on the most recent trends estimate that a further 14 million ha of land will be brought under irrigation by 2025 (Figure 1), and an additional 10 million ha by 2050 (Amarasinghe et al. 2007). Consequently, the Business as Usual Scenario projects that 31 km^3 of additional groundwater withdrawals will occur by 2025, and a further 22 km^3 by 2050. The result will be that by 2025 and 2050 India would be withdrawing 75 % and 85 % of the sustainable groundwater supply, respectively, accounting for both natural and return flow recharge. With this, several river basins would become water scarce and the rate of use would be unsustainable. In fact, 10 basins will withdraw more than 75 % of their available groundwater supply, and these 10 basins account for 69 % of the total groundwater supply in India.

On the other hand, if groundwater withdrawals are to remain at the 2000 level, then the additional surface withdrawal requirement will need to increase further by 65 km^3 by 2025, in part because surface water systems are less efficient than groundwater based systems. The peninsular basins, some of which are already water scarce, will require more than half of the total additional surface water withdrawals projected for the country, which is more than 35 km^3. Given the past investment trends and the slow growth of canal irrigation in recent decades, it is difficult to envisage adding this quantity of surface water in the next 25 years. Furthermore, such demands cannot be met in the peninsular rivers without diverting from elsewhere.

Figure 1. Groundwater irrigated area and withdrawal projections.



Source: Irrgated area data of 2000 are from GDI 2005.

In either case, whether through rapid expansion or an unexpected slowdown of further groundwater use, a major water crisis in the water sector is pending unless immediate solutions are sought. Next, we discuss some policy options that can avert a crisis in the short to medium term.

Policy Options

From overall economic investment perspective groundwater has been a much cheaper option than surface water development, although if sustaining and further development of the resource requires major investments in recharge and perhaps even large-scale transfers of water to where the recharge is required. Also with rising energy prices, the cost of groundwater abstraction will increase. At present, the development of one ha of surface irrigated area costs more than three times the cost required for developing one ha of groundwater irrigated area (GOI 2006). Groundwater development has been generally undertaken by the private sector with users sharing a significant part of the cost. Moreover, groundwater irrigation also generates higher crop production benefits, provided that adequate groundwater stocks are available to ensure reliability.

Sustaining Groundwater Irrigation

Artificial groundwater recharge could enhance the groundwater stocks, have positive impacts, and generate various social and environmental benefits. As has been practiced in some developed countries, India can start to actively manage its aquifers. Presently it depletes its groundwater stocks before the monsoon months and then recharges these with the monsoon run-off (Shah 2007). Existing small tanks and ponds, numbering more than 500,000 throughout

India, which are already augmenting the natural groundwater recharge, can be modified to further increase recharge, while meeting the drinking water demand for the human beings and livestock (Sakthivadivel 2007). Also, new small tanks and ponds need to be designed and constructed with a view to optimizing groundwater recharge, where appropriate. However, we need to know more about the negative impacts of groundwater recharge on downstream users before embarking on large-scale recharging programs, especially in water scarce river basins. Also the underlying hydrogeology will dictate whether recharge will result in improved supplies of groundwater in a form which can be appropriately utilized.

Rainwater harvesting programs, such as *johads* in Alawr district in Rajasthan (Sakthivadivel 2007) and also groundwater recharge movements in Saurashtra and Kutch (Shah and Desai 2002), have proven to rejuvenate the groundwater resources available for irrigation. However, some interventions, such as rain water harvesting in the upstream catchments, have been shown to reduce the inflows to existing reservoirs downstream (Kumar et al. 2006a), and can incur more cost than the benefits they generate.

The existing knowledge on surface and groundwater interaction across river basins in India is generally site-specific and neither sufficient to identify the locations where such negative impacts can occur nor, in fact, to determine where and how to improve groundwater recharge. Further research is required to identify the locations where artificial groundwater recharge harnesses water; the quantity of water that can be harnessed and the extent to which it meets the additional demand; and the net social benefits that these programs generate.

Increasing groundwater irrigation efficiency by an additional 5 % from the level assumed under the BaU scenario (70 %) can reduce the additional groundwater demand in 2025 by about 20 km^3 or two-thirds, assuming that these savings result in savings at the basin scale. Recent research shows that modern irrigation technologies — sprinklers and drip irrigation — are operating at 70-85 % efficiency in some irrigation systems in India (Kumar et al. 2006b, Narayanmoorthy 2006). Modern irrigation technologies also improve the uniform distribution of the irrigation water, reduce non-beneficial transpiration, and in general have higher productivity than the traditional flood irrigation methods. However, adoption of these technologies in India has been very slow. And these technologies were mainly adopted for a few crops, such as fruits and vegetables, in the groundwater irrigated areas (Narayanamoorthy 2006; Kumar et al. 2006b). Further research and extension are needed to determine the potential of such irrigation technologies in the Indian context, their net economic benefits and practical modalities to scale them up where appropriate. In addition, it is imperative that it be determined that these interventions would result in actual water savings, and not result in the transfer of water from other users further down the basin, as has been the case elsewhere.

Reducing uncontrolled groundwater pumping could mitigate over abstraction in many basins. In 2000, India withdrew about 273 km^3 of groundwater to meet only 151 km^3 of crop consumptive water-use demand. Indeed, proper policy and institutional interventions can reduce over abstraction even when traditional irrigation methods are utilized. Formal or informal water markets (Somanathan and Ravindranath 2006; Banerji et al. 2006), and regulating and/or providing a reliable rural electricity supply (Shah and Verma 2000) have been shown to have some effect on controlling unnecessary pumping and increasing water-use efficiency. Replicating these interventions, with adjustments to satisfy local socioeconomy, could help arrest the uncontrolled groundwater pumping in many water-stressed river basins.

Improving Crop Productivity

Improving crop productivity presents the greatest opportunity for reducing the additional irrigation requirement. If water productivity stagnates at 2000 levels, India will require 1,029 km^3 by 2050 to meet the agricultural consumptive water use demand, which is in effect the same as the estimates of total potentially utilizable water resources of India, and simply unattainable. Therefore, it is imperative that the productivity of water be continuously increased. India's grain crop water productivity - 0.64 and 0.34 kg/m^3 of consumptive water use for irrigated and rain-fed areas, respectively - is, in comparison with other countries, stubbornly low. The water productivity of non-grain crops under irrigated and rain-fed conditions is also low, and vary significantly across districts (Table 1).

Table 1. Irrigated, rain-fed and total water productivity of grain and non-grain crops.

State	Water productivity (WP) of grain and non-grain crops								
	Irrigation			Rain-fed			Total		
	Grain area as a fraction of total	WP of grains	WP of non-grains	Grain area as a fraction of total	WP of grains	WP of non-grains	Grain area as a fraction of total	WP of grains	WP of non-grains
	#	$\$^*/m^3$	$\$/m^3$	#	$\$/m^3$	$\$/m^3$	#	$\$/m^3$	$\$/m^3$
Andhra Pradesh	0.76	0.17	0.41	0.45	0.11	0.72	0.59	0.16	0.56
Assam	0.99	0.22	0.19	0.78	0.10	0.72	0.79	0.11	0.72
Bihar	0.93	0.13	1.66	0.86	0.14	1.43	0.90	0.13	1.55
Chattisgarh	0.95	0.10	1.47	0.91	0.10	0.50	0.92	0.10	0.69
Gujarat	0.37	0.08	0.23	0.45	0.12	0.57	0.42	0.10	0.31
Haryana	0.76	0.17	0.16	0.84	0.12	1.37	0.77	0.17	0.19
Himachal Pradesh	0.89	0.13	2.28	0.85	0.13	1.99	0.86	0.13	2.03
Jammu and Kashmir	0.81	0.13	1.34	0.88	0.14	4.10	0.85	0.14	2.43
Jharkhand	0.71	0.11	2.18	0.91	0.11	0.83	0.89	0.11	1.17
Karnataka	0.60	0.15	0.34	0.69	0.12	0.63	0.66	0.13	0.44
Kerala	0.50	0.16	0.39	0.09	0.16	0.83	0.17	0.16	0.78
Madhya Pradesh	0.87	0.07	0.36	0.56	0.10	0.40	0.64	0.09	0.39
Maharashta	0.56	0.07	0.51	0.67	0.08	0.21	0.65	0.07	0.34
Orissa	0.83	0.11	1.44	0.75	0.07	0.72	0.77	0.09	0.89
Punjab	0.87	0.25	0.24	0.57	0.13	4.21	0.86	0.24	0.39
Rajasthan	0.59	0.07	0.20	0.84	0.07	0.36	0.75	0.07	0.24
Tamil Nadu	0.64	0.20	0.49	0.55	0.22	1.09	0.60	0.20	0.64
Uttar Pradesh	0.83	0.15	0.26	0.80	0.14	2.12	0.82	0.14	0.44
Uttaranchal	0.73	0.20	0.25	0.91	0.11	1.26	0.83	0.15	0.35
West Bengal	0.85	0.21	1.23	0.66	0.17	1.17	0.73	0.19	1.18
India	0.76	0.15	0.36	0.68	0.11	0.69	0.71	0.13	0.50

Source: Authors' estimates are based on PODIUMSIM methodology.

Note: * - Values of crop production, estimated using the average (1999-2000) of the unit export prices of crops in the FAOSTAT Database (FAO 2005) are used to make comparison between the grain and non-grain crops.

By increasing grain crop water productivity by 1.0 % per annum, the respective CWU could be maintained at present day levels while meeting the increased demands for grain. Increasing the productivity a little further, to 1.4 % annually, would even account for the CWU demand for all crops (Amarasinghe et al. 2007). These scenarios demonstrate a significant opportunity to avoid a future agriculture-driven, water crisis. The latter scenario is equivalent to doubling the yield over the next 50 years, which given the past trends in India, is setting a very high goal. On the other hand, given the remarkable achievements of other countries over the last few decades, India does have the potential.

India's research and technological capacities are increasing. Knowledge generation in new commodity research, remote sensing, geographic information systems, and advances in water management systems are second to none in developing countries. India also has a sound agricultural research system spread across all regions. The immediate focus then should be how to combine these rich resources with proper extension systems to promote rapid growth in crop productivity. India needs to effectively use the advances in research and technology to identify opportunities for high productivity and also high potential zones for different crop and livestock production systems. As the value of water is increasing, agricultural production systems should be promoted in zones where they have a high value for each drop of consumptive water use and where there is adequate water supply for irrigation, such as in the lower part of the Ganga Basin. The recent trends of agricultural diversification, which are associated with changing consumption patterns, should also facilitate this revolution.

Agriculture Diversification

Agricultural diversification**,** if properly planned, could also help reduce additional irrigation demand. The BaU scenario projections, as discussed in the previous two chapters, show that the increasing consumption of animal products is transforming the demand and the production patterns of cereals (Table 2). Over the period (2000-2025), maize, primarily for livestock feeding, will contribute to more than one-third of the total grain demand increase (45 %). Between 2025 and 2050, this contribution is expected to be 83 % of the total grain demand increase. Also, food demand for high value non-grain crops, such as oilseeds, vegetables and fruits, is also increasing. The share of the value of non-grain crop production is expected to increase, from 51 % in 2000, to 63 and 69 % by 2025 and 2050, respectively.

As a result of the changing consumption patterns, food production patterns will change. The production of irrigated non-grain crops, as compared with irrigated grain crops, will increase much faster. According to the BaU scenario, as much as half the irrigated area will be under non-grain crops by 2050, compared with only 29 % in 2000; 71 % of the crop production (grains and non-grain crops) will be produced under irrigation by 2050, compared with 67 % and 51 % in 2000. Major implications of this agricultural diversification are that

- the consumptive water use demand of grain crops, in comparison to non-grain crops, increases very slowly;
- with increasing reliance on groundwater and increasing water-use efficiency of groundwater, the irrigation demand for grain crops will decrease from the 2000 levels (Figure 2); and
- almost all additional irrigation demand will be for non-grain crops, and much of that will be from groundwater (Figure 3).

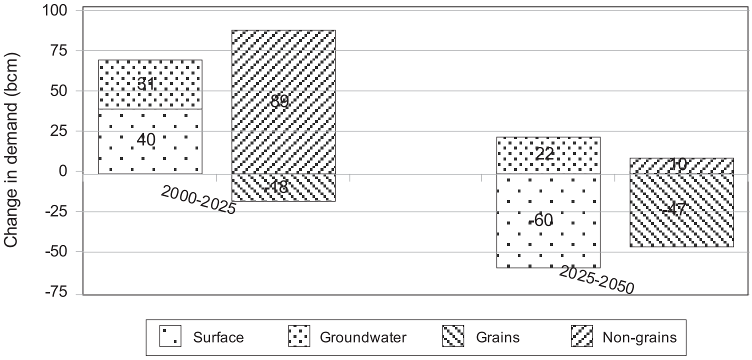
Table 2. The demand and production of grain and non-grain crops with their irrigation requirements.

Crop	Crop demand[i] (million tonnes)			Crop production Total[i] (million tonnes)			Crop production Share from irrigation (%)			Irrigated crop area (million ha)			Irrigation requirement[ii] (net-evapotranspiration) (km³)			Irrigation withdrawals (km³)		
	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Grain crops																		
Rice	82	109	117	89	117	143	69	70	71	24.1	25.0	26.0	74	73	72	261	239	207
Wheat	67	91	102	72	108	145	95	99	99	23.0	25.0	26.3	64	72	76	132	135	122
Maize	16	50	121	12	28	65	32	51	38	1.4	4.0	5.1	1	3	3	3	5	6
Other cereals	21	23	16	19	21	13	14	19	38	2.2	2.4	2.7	5	5	6	10	9	9
Total cereals	187	273	357	193	274	365	71	76	75	50.8	56.4	60.1	144	153	158	406	388	344
Pulses	14	18	21	13	18	19	17	17	18	2.8	2.9	2.8	6	6	5	11	10	8
Non-grain crops																		
Oilcrops	48	103	133	31	73	97	31	56	68	6.1	18.7	25.2	13	37	49	25	66	76
Vegetables	75	150	189	74	149	227	44	64	69	1.7	3.3	3.8	3	5	6	6	10	10
Fruits	47	78	123	46	83	106	46	60	63	1.7	3.0	4.0	5	9	12	10	16	18
Sugar	26	42	55	30	46	60	94	93	100	4.2	5.1	6.6	41	48	60	80	87	95
Cotton	2	4	6	2	4	6	50	65	71	3.0	5.9	7.9	16	28	38	31	50	59
Other crops	-	-	-	-	-	-	-	-	-	5.6	11.3	7.3	18	26	18	36	48	28
Total grains	52[i]	73[i]	90[i]	54[i]	74[i]	93[i]	67	72	72	53.6	59.3	62.9	149	159	163	417	398	352
Total non-grains	106[i]	198[i]	284[i]	96[i]	187[i]	266[i]	51	65	71	22.3	47.2	54.8	95	154	183	188	277	286
Total	158[i]	272[i]	374[i]	150[i]	261[i]	359[i]	57	67	71	75.9	106	117	245	313	346	605	675	638

Source: Authors' estimates based on PODIUMSIM

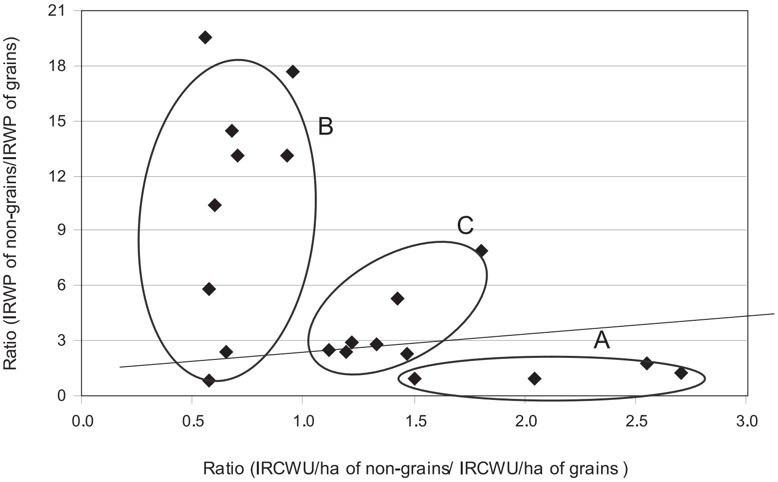
Notes: [i] Total demand and production for grain and non-grain crops are estimated using the average 1990-2000 export prices.
[ii] Irrigation requirement or net evaporation is the difference between evapotranspiration and effective rainfall.

Figure 2. Change in demand in surface and groundwater irrigation for grain and non-grain crops.



Source: Authors estimates

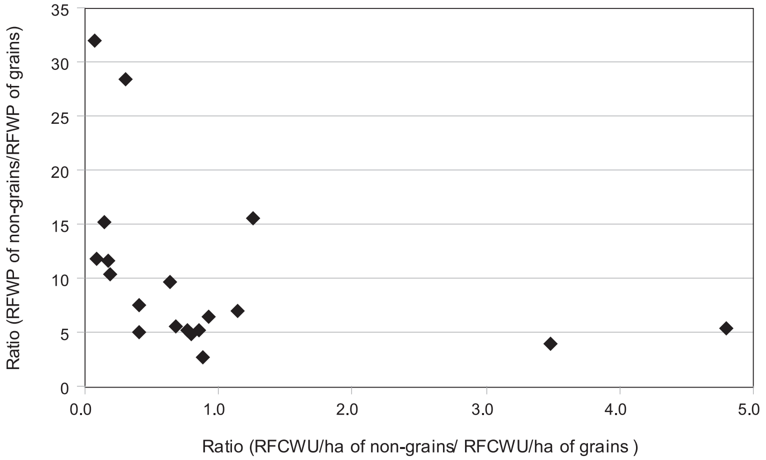
Figure 3. Consumptive water use/ha and water productivity differences between grain and non-grain crops in irrigated areas of different states.



Most of the non-grain crops, usually produced for urban markets or for export, can bring in high returns. However, in order to reap these benefits, high-value crops require the timely application of expensive inputs. A reliable irrigation supply is a critical prerequisite for timely input application, and also, it is an input by itself in water- stressed crop growth periods. More recently, groundwater has been the major source of this reliable irrigation supply in the context of diversifying agricultural production. It is likely that this trend will continue, at least into the near future. Therefore, an immediate challenge is to identify the cost-effective physical and institutional interventions for sustaining the groundwater irrigation growth.

Agricultural diversification could also be promoted in conjunction with improvement in water productivity. Figure 4 shows a glimpse of where this can be done at the state level. For the case of irrigated crops, the X-axis in Figure 3 is the ratio of the CWU (m^3/ha) for non-grain and grain crops, and the Y-axis is the ratio of the water productivity (US$/$m^3$ of CWU) for non-grain and grain crops. Figure 4 shows the same ratios for rain-fed production.

Figure 4. Consumptive water use/ha and water productivity differences between grain and non-grain crops in rain-fed areas of different states.



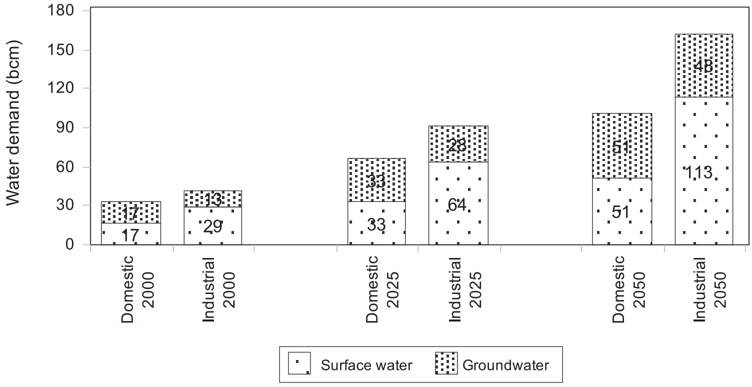
For the irrigated conditions there are three distinct clusters (Figure 4). The states in cluster A, that is Punjab, Haryana, Uttar Pradesh and Uttaranchal are those areas where irrigation is dominant and yields of grain crops are generally high. Also the CWU/ha for non-grain crops in these areas is significantly higher than for grain crops, but have lower productivity in terms of value per cubic meter of water. The difference between the water productivities of irrigated grain and non-grain crops is relatively small. Crop diversification in states in this cluster according to the current cropping patterns may yield little or no benefits. These states can continue to grow grains, increase the yields and trade the production surplus with other states as has been the case in the past. The benefit of that per every cubic meter of water depleted could be as high as the benefits that non-grain crops generate.

The states in cluster B are mainly in the east, namely Assam, Orissa, West Bengal, Bihar, Chhattisgarh, Jharkhand and also Jammu and Kashmir in the north and Kerala in the south. These states have significantly high irrigated areas under grain crops and a substantial part of that is rice. However, the rice crop has low yields and higher CWU than the irrigated non-grain crops in the state. Thus, this group has the highest potential for improvements in water productivity in grain crops. Many states in this group are also relatively water abundant, and they can continue to grow water intensive grain crops and increase water productivity through growth in the yield. On the other hand, due to limited land resources many small to medium land holders are poor in these states. So, crop diversification can also generate substantial benefit to these farmers. Cluster B states should have a combined strategy, increase the yields of grain crops while diversifying cropping patterns in small to medium land holdings with low productivity. The production surpluses of non-grain crops in this cluster can meet the production deficits of the states in cluster A.

In cluster C, states like Tamil Nadu, Andra Pradesh, Karnataka, Maharashtra, Madhya Pradesh and Gujarat, and Rajasthan, are relatively water scarce than those in cluster B. Irrigated non-grain crops in these states consume more water than the grain crops, but generate significantly more benefits. Crop diversification can benefit these states the most. It should be promoted as a solution in medium-term to meet the increasing agricultural water demand and also to meet the increasing demand for non-grain food crops and feed grains.

Rain-fed non-grain crops in all states have significantly higher water productivity than rain-fed grain crops (Figure 5), and many areas will benefit from crop diversification. On the other hand, major rain-fed states also have very low productivity compared to irrigated crops. These states have a significant scope for increasing crop yields. A small quantity of supplemental irrigation in the critical period of the crops' growth could even double the rain-fed yield (Sharma et al. 2006).

Figure 5. Domestic and industrial water demand projections of India.



Source: Authors estimates

Though the above analysis is constrained by the fact that the analysis was done at the state level, it demonstrates that there is a scope for improvements in productivity and crop diversification. An analysis at a smaller spatial unit, such as district or sub-basins, should provide a better picture where these improvements can de done and what interventions required. A preliminary analysis shows that a significant variation of water productivity exists across districts and also across different land-use patterns. A more detailed analysis at the district level, combining information on climate, physical and institutional factors, and geo-hydrological variation should provide a more rigorous estimate of the likely extent of crop diversification and growth in water productivity.

Contingencies for Large Interbasin Water Transfers

As discussed elsewhere in this paper, there are a number of policy options which could serve to replace, supplement or compliment aspects of the NRLP while addressing India's future water needs for food production and the other sectors. That said, there are situations where major interbasin transfers will be inevitable, especially over the long term. The justification and necessary support for such investments is unlikely to come from the development of new irrigated areas, at least not as a significant part of the investments, but more likely from a combination of increased domestic and industrial water demand, providing a reliable water supply for high-value crops, growing pressure on the groundwater systems, escalating energy prices, and from increased efforts to account for environmental needs. In each case, the characteristics and timing of such developments will depend on socioeconomic, environmental, and agricultural conditions within the given basin and locality.

Domestic and Industrial Water Demand

The demand of water in domestic and industrial sectors, according to the BaU scenario, will increase several fold over the period 2000-2050 (Figure 5). Domestic water demand is projected to increase by 204 % over the period 2000-2050, and the industrial water demand will increase by 234 % over the same period. It is expected that these sectors will generally secure their water from surface water sources, and given the expected increasing affluence of both sectors, the users will be able to pay for a reliable and high quality surface water resource. Some of this may result from reallocating from the agriculture sector. However, increasing the demand for surface water of both the sectors (118 km^3 over the period 2000-2050) is expected to outpace the reallocation from the irrigation sector. Over this period, surface irrigation demand is expected to decrease by 20 km^3, according to the BaU scenario, but this would still require that a further 100 km^3 of surface water supply be developed for domestic and industrial sectors. A substantial part of this additional surface water supply is projected to be for states that are already on the physical water scarcity threshold. These states are Andra Pradesh, Tamil Nadu, Gujarat, Maharashtra and Karnataka, where water availability for further development is a severe constraint or the cost of further development is prohibitively expensive if it has to be conveyed from distant locations. So these states, even under the BaU growth patterns, may require some intra - or inter - basin water transfers to meet the demands of domestic and industrial sectors. In addition, groundwater depletion in most of these states is already high, and further development of this resource for irrigation will exacerbate this situation, and increase the tension between agriculture and other sectors.

It is also likely that India's industrial and service sectors could shift gear and grow much faster than envisaged in the BaU scenario. The BaU scenario assumed that the per capita gross domestic product (GDP) will, on an average, grow at 5.5 % annually, and the contribution from the industrial and service sectors will further increase. Given the present economic growth patterns (9 to 10 % GDP growth), these assumptions are conservative. Many of the well to do states, with better industrial infrastructure now, will inevitably contribute more to a scenario of high industrial and service sector growth. And, many of the water scarce rich states may be willing to pay water rich poor states to meet their future water requirements, thus creating the conditions to both finance and develop large interbasin water transfers, similar to the situation with the Lesotho Water Highlands Project (Shah et al. 2007).

Agricultural Diversification

It is imperative that India needs to diversify its agriculture to meet future food demands. Much of the diversification will be towards high-value agricultural products. Returns from surface irrigation systems at present are very low because much of the command areas grow food grains, while high-value crops are grown outside the command areas using groundwater. Crop diversification could change the chronic low productivity of these systems, but only if a reliable water supply can be secured. There are already movements of growing high-value crops with a reliable water supply for urban markets or export. Should this gather momentum, water scarce southern and western India, with their increasing income from high-value agriculture, may be willing to invest for interbasin water transfers. However, if low productivity of these surface irrigation systems persists, and further irrigation sources have to be developed, including interbasin transfers to meet the demands for high-value crops it will be a significantly more expensive solution both in terms of economics and water resources.

Rising Cost of Energy

Irrigation expansion in India in the last two decades was primarily due to small-scale lift irrigation systems using mostly groundwater, but also surface water. These systems are highly flexible and provide reliable irrigation supply on demand. Yet, this mode of irrigation development is, in most cases, highly energy intensive. So far, the energy supplies of many states are highly subsidized. But the cost of energy, whether it be in the form of electricity or diesel, has been rapidly increasing in recent times. States can no longer continue to provide subsidies on electricity as they are an impediment to economic growth in other sectors. As energy prices increase, the farmers may opt for direct surface water for irrigation or reduce their pumping costs by groundwater recharge. Thus, rising energy cost could be another condition from the agriculture sector that supports, to some extent, the development of large-scale interbasin water transfers. Conceivably there could also be an indirect argument for interbasin transfers where concurrent development of hydropower could provide increased supplies of electricity, however, from an economic perspective this new power source would be better utilized in the industrial and service sectors.

Conclusion

Increasing agricultural water productivity offers one of the greatest opportunities to reduce the demand for additional irrigation. By doubling the water productivity over the next five decades, no additional irrigation would be required, at least on-balance. The achievement of this will require major investments in research, development, extension on better management of other inputs, and infrastructure particularly to improve the reliability of water supply.

Crop diversification offers opportunities to increase the value produced by the same amount of water, which would be particularly important in the water scarce basins in peninsular India. Crop diversification in already high water productivity areas, such as in north and north west, will need further understanding as the water productivity is already high for grain crops. In the water abundant east there is considerable scope to increase the productivity of grain crops, yet crop diversification would help the poor small farmers increase their returns from their land.

Based on recent trends, groundwater will continue to be the source of choice for further development of irrigation for the foreseeable future. However, in an increasing number of basins, aquifers are becoming over exploited. Continuing along this business as usual pathway means that India is heading for an increasing number of regional water crises. Depending on the specific conditions, artificial recharge could significantly enhance groundwater supplies. Such interventions should include renewed efforts for small scale water recharge systems, but also carefully consider large scale facilities, including as components of inter - basin transfer projects. The implementation of any large scale programs or interventions must determine, among other things, the hydrogeological suitability, the likely negative implications on the downstream water users, and the relative economic viability. Increasing groundwater irrigation efficiency and other demand management strategies will also be helpful for reducing the groundwater over-abstraction.

While it is acknowledged that the interactions between the surface and groundwater resources will be different for a given basin and the dynamics will very much depend on how these resources are developed, the important point to emphasize is that the policy environment for water resources management in India must take into account the present realities, and allow for not only the realistic future demands, but the real constraints of the availability of the resource. Specifically, much more emphasis needs to be placed on effective management of the groundwater resources through enhancing the supply by artificial recharge and conservation. Also, revived efforts should be made to improve the existing surface irrigation systems, in particular to reconfigure the systems to provide more reliable water supply and allow effective community level management, where appropriate. To achieve this requires a level of study and investigation beyond what has been hither to done in most situations.

Further development of groundwater, and water savings and reallocation of water from the agricultural sector will not be sufficient to meet the water requirements of other sectors. The increasing capacity and willingness of the domestic and industrial sectors to pay for clean and reliable water supply would increase the pressure for further surface water resources development. Such conditions are likely to emerge soon in states with high economic growth, particularly in the basins that are water scarce. Most of these are located in peninsular India, and meeting the additional surface water demand in these basins may require large intra - or interbasin water transfers.

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Part II

Demographic Projections for India 2006-2051: Regional Variations

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Introduction

The size and growth of population in India and in many other developing countries of the world was not a serious concern of the planners and administrators until the first quarter of the last century. Even during the second quarter of the last century, the rapid population growth in many of the developing countries was not taken seriously. It is only during the third quarter of the last century that the growth of population in India and in many other developing countries started showing its serious consequences on their resources. Population stabilization has thus emerged as a major agenda, particularly in the context of acute pressure on agricultural resources and urban facilities.

Planning for the future requirements of the population, therefore, has become the major concern of the planners and requires accurate estimates of the future population growth. United Nations and several other national and international agencies, therefore prepare population projections and keep on updating them as and when fresh information becomes available. For India main projections in the recent past have been prepared by United Nations, Expert Committee of the Planning Commission, Population Foundation of India (Natrajan 2000) and Population Council (Visaria and Visaria 1996)

A review of these projection exercises reveals that the figures vary extensively depending on the developmental parameters incorporated in their models. Importantly, the National Commission for Integrated Water Resources Development (NCIWRD 1999) has taken estimates given by Visaria and Visaria 1996 as the ‘higher side variant’ (1,581.00 million) and those of the United Nations 2006 as the ‘low side variant’ (1,345.90) for the year 2050. These have then been used for making future estimates of food requirement for the growing population in the country.

The projections, providing the basis for the analysis undertaken by the Commission, suffer from two major limitations: (a) both the projections were made prior to 2001 and therefore did not have the benefit of the data provided by the Census of India 2001, with regard to the size and its age structure, geographical distribution, estimate of fertility and mortality etc., and base their projections on the basic age structure and the total population given a decade ago by the Census of India 1991, and (b) none of the projections had been made giving due consideration to the impact of the HIV/AIDS on the expectancy of life and other demographic parameters.

Another important limitation of almost all the population projections from the planning point of view is that they do not give projections at micro level such as districts. Natrajan and Jaychandran's district level estimates are among few such projections which suffer from the fact that they also use the base year data prior to 2001.

In the present paper an attempt has been made to prepare the fresh country level population projections by incorporating the age structure of the population given by the GOI 2003. Also, at country level projections have been made which take into consideration the impact of HIV/AIDS on the future estimates of mortality. These projections have been made for average and high variant of fertility with HIV/AIDS and without HIV/AIDS.

These projections have been made for quinquennial periods: from 2001 to 2051 – Cohort using Component method has been used. After making the all India population projections the state wise population projections have also been prepared by using the state level base population figures provided by GOI 2003 and projected figures of fertility and mortality used by Natrajan and Jaychandra after adjusting them for the Sample Registration System (SRS) figures of 2001. They have used the time series data of TFR provided by the Sample Registration System (1971-1996) and using the mid point of 1983 as origin have projected the TFR values from 1996 to 2051 using the least square linear regression fit. They also assume that once the TFR of a state reaches 1.6 it can not further fall down from this level, the criterion used in the present case also. These estimates are quite reliable as they use the data of a time series ending very close to 2001. However, on comparing their estimate of TFR for 2001 with the actual estimates of 2001 provided by SRS, it was found that the two differ marginally. It was therefore considered appropriate to adjust the figures accordingly.

While making the population projection only two variants have been attempted: average and high variants. The average variants correspond to the TFR generated by the regression line. For the high variant of population projection, the upper limits of the 99 % confidence interval of the TFR were chosen. In view of the relatively stable values of the life expectancy, it was considered to keep them constant for both the projections.

In the second section of the paper the population projections are made for the major states of India using the same methodology as mentioned above for the country as a whole. At the state level, however, the effect of HIV/AIDS was not estimated due to the considerations of accuracy.

Methods of Population Projection

Methods of making population projections can be classified mainly into following two methods:

1. Cohort Component Method
2. Mathematical Methods

Cohort Component Method of Population Projection

Growth of population in an area basically depends on births, deaths and net migration of people during the period under consideration. The estimate of births and deaths is possible only when the estimates of fertility and mortality parameters of the population are available. For fertility, the parameters are age specific fertility rates (ASFR) and gross reproduction rates (GRR). For mortality projections one would require life expectancy or longevity of life **(**e0**)** and the corresponding Life table to give age specific survival ratios. In case the population for which projection is being made is open to migration, estimates of migration are also needed. The basic task involved in population projection, therefore, is the projection of the future levels of fertility, mortality and migration rates, if the population is open for migration.

Component method of population projection involves separate projection of the number of males and females in different age groups. This method takes into account separately future course of fertility, mortality and migration and is therefore considered more accurate than any mathematical method based on past trends. The ability to provide age sex break up of the projected population is an added advantage of this method. The method requires the following data:

- initial population with age and sex break up;
- past trends in mortality and assumptions about future trends in terms of survival ratios by age and sex;
- past trends in fertility and assumptions about future trends; and
- past trend of migration and future assumption about its change.

A large majority of developing countries do not have reliable data on many of the above aspects. Consequently, appropriate estimates are to be obtained in place of actual data, based on certain assumptions. The assumptions made in such exercises are briefly discussed below.

Initial Population

It is noted that the data related to actual population invariably suffer from both content and coverage errors. Research studies by Coale and Hoover 1958, ORG Group 1974, Cassen and Dysen 1976 etc. begin by correcting population figures before using them for making their projections. The basic assumption in this regard is that population growth will follow a smooth curve over time and also from one age to another.

Mortality

The basic approach in the component method is that the survivors of the population of one age group will move into the next age group over time. It should, therefore, be possible to obtain the number of persons in an age group at a given point of time by projecting the number of survivors from a preceding (appropriate) age group. This, one can compute by multiplying the survival ratios worked out from a Life table to the population in the preceding age group. Thus, choosing a Life table is a critical task in any exercise of population projection. For the countries for which a reliable Life table is not available, scholars have used the Model Life Tables prepared by the United Nations. Keeping in view the differences in the regional mortality patterns, separate sets of Model Life Tables have been prepared for major regions in the world. Among these, one can select a typical Life table suitable for the country. The figure of life expectancy (e0), which is a powerful summary statistic of the Life Tables, is often very helpful in the selection. Future changes in the level of mortality can also be affected by changing the values of life expectancy.

Fertility

For estimating the number of births during a given period, we need the information on the fertility behavior of the population as reflected by Age Specific Fertility Rates (ASFR) of the female population. Assumptions about ASFR are made in terms of Gross Reproduction Rates (GRR) or Total Fertility Rate (TFR). TFR is a measure showing the average number of babies born to a couple during their whole span of reproductive period. A value of TFR=2.1 is generally taken as replacement level of fertility.

Migration

It would be important to consider international migration when population projections are to be made at national level. However, in view of the fact that this is not very large in India, we may choose to ignore this factor. However, for making the projections of urban population, the assumptions about rural to urban migration would be critical. As migration is one of the most complex phenomenon in population studies and is governed by a host of socioeconomic factors, determining the trend and the absolute number of immigrants into urban areas will be extremely difficult. Notwithstanding the problems, one must make an attempt to determine the migration trend based on most likely socioeconomic configuration.

Mathematical Methods

For population projections, generally two types of methods are used: Exponential and Logistic.

Exponential Growth Method

In case the detailed information required for component method of population projection is not available or if only broad estimates are required without the age and sex break up, it is possible to make population projections with the help of the past trends determined statistically using the past data. This would involve fitting a mathematical curve or a regression line to the time series data on population. One can compute the population figures for a future time point by extrapolating for the future values of time.

Logistic Growth Method

Due to natural and other constraints, it is argued that population growth can not go on indefinitely and certain internal checks are likely to emerge from within the system slowing down the growth rate and bringing it to the equilibrium vis–a-vis the resources. Population analysts also observe that the growth curve of a population follows an exponential path only for a short period of time, say 30 to 40 years. Consequently, when it comes to projecting the population for a longer period of time, there has to be provision for the stabilization of the population. Logistic functions that have this inbuilt characteristic, are, therefore, noted as useful in making long term projections of a population. The advantage of the logistic function is that it can stabilize the population at an exogenously determined upper limit.

Population Projections for India 2001 -2051

As pointed out earlier the population projections made so far have depended on the data provided by the census of India 1991. Since the results of the population census of 2001 are available there is a need to update the projections by using the latest figures for the parameters of fertility and mortality and the base population with its age-sex break-up.

Base Population

The latest age data for male and female for the country, provided by the GOI 2003, which constitutes the basis of our projection exercise, is given in Annex Table 1.

Assumption about Mortality

Dyson and Hanchate have incorporated the effect of HIV/AIDS on the future mortality rates in making their population projection for India. This hopefully would bring the projected figures closer to reality as the country is witnessing a high incidence of HIV/AIDS which is showing a steep rise in recent years. The methodology adopted by these scholars is in line with that of a UN study which has empirically determined the relationship between the prevalence rates of HIV/AIDS and the reduction in the life expectancy (e0), using the data of only six countries where the prevalence rate was below 2.0 % (UN 1999). Based on this scanty data set, Dyson and Hanchate have assumed that while the life expectancy will continue to increase in future, the actual achievement during a period of about 15 years (starting from 1998 to that of 2011-2016) will be less by 1.7 years over the projected figure for males. Similarly, actual life expectancy for females during 2011-2015 is taken to be less than the projected figure by 0.9 years.

It may be argued that the impact of HIV/AIDS incorporated in the model is somewhat on the higher side. We have computed the life expectancy figures, as given in Table 1, based on the values estimated by Natrajan and Jayachandra. Adjustments have nonetheless been made in these values to take into consideration the impact of HIV/AIDS. However, unlike Dyson and Hanchate, the decline has been assumed here to be somewhat less. Male life expectancy is projected to decline by 1.7 years over a period of 25 years. It is implied that the disease will bring down life expectancy by 0.34 years in every 5 years from 2001 up to 2026 (0.34*5= 1.7). From 2026 to 2051, the decline would be 1.5 years only, the five yearly decline being 0.3 years only (0.3*5=1.5). In case of females, too, the values have been reduced at a lower rate (than according to Dyson and Hanchate), keeping in view their lower status and prevailing family norms, which are responsible for lower spread of the disease among women in India. It is assumed that AIDS will bring down life expectancy at a flat rate of one year in every 20 years. These life expectancy figures are given below in Table 1.

The lower impact of the epidemic can be justified in terms of growing awareness about the disease, precautionary steps by the public and non governmental agencies and the considerable medical and food aid being provided to the affected people, as reported by National Aids Control Organization (NACO). Also, the higher impact as proposed by Dyson and Hanchette is based on the scanty data of a few countries that have a significantly larger proportion of reported cases. The spread is likely to be less during the following decades also because the channel of communication through the clients of the

Table 1. Projected values of life expectancy after incorporating the effect of HIV/AIDS.

	Year	2001	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Male	eo	62.9	62.9	66.5	66.5	68.9	68.9	70.7	70.7	72.3	72.3	73.5
	Reduction due to HIV	0.34	0.68	1.02	1.36	1.70	2.00	2.30	2.60	2.90	3.20	3.50
	eo with HIV	62.56	62.22	65.48	65.14	67.20	66.90	68.40	68.10	69.4	69.1	70.00
Female	eo	64.9	64.9	69.7	69.7	73.5	73.5	76.3	76.3	78.5	78.5	80.4
	Reduction due to HIV	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75
	eo with HIV	64.65	64.40	68.95	68.7	72.25	72.0	74.55	74.0	76.25	76.0	77.65

female sex workers to their family partners has not yet become alarming, as revealed by the low proportion of females among the reported cases in India. All this would justify our optimism with regard to slightly higher life expectancy than allowed in the LH model. Further, it is assumed that life expectancy would stabilize after 2051. Finally, we have taken UN model south Asian life table, which matches the pattern of mortality in most of the countries of the region including India.

Assumption about Fertility

Natrajan and Jayachandran have used the past trends of TFR from 1982 onwards and have fitted a linear regression equation between time and TFR. On the basis of this equation, they have projected the future values of TFR up to 2050. These estimates of TFR are 3.0 in 2001 and are 1.8 for 2050. As the population projections are sensitive to the fertility estimates and the projected regression estimates are only the average values, there is a need to have some alternative estimates. Considering the regression estimates of TFR to be the average, the higher variant of the estimates has been generated from the upper limits of the 99 % confidence intervals in each case. These two values of the estimates of TFR are given below in Table 2.

Table 2. Estimated values of TFR by low and high variant, 2001-2050.

Year		2001	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
TFR	(average)	3.0	2.7	2.5	2.4	2.2	2.1	2.0	2.0	2.0	1.9	1.8
	(High)	3.17	2.9	2.7	2.6	2.4	2.3	2.2	2.2	2.2	2.1	2.1

Assumption about Migration

The effect of international migration on the estimated population would be marginal. It has, therefore, been decided to ignore this factor in making population projections, as mentioned above.

Projected Population of India 2001 -2051

Using the gender and age distribution of the population for 2001, the parameters of mortality with and without HIV/AIDS and the two variants of fertility, projections for population have been made based on the cohort component method. Population estimates have been obtained for each decade from 2001 up to 2051. We obtain a high as well as a low variant of the populations, with and without HIV/AIDS. These projections are given in Table 3 and Table 4 below. The projections are also represented by the bar diagrams given in Figures 1 and 2.

Table 3. Population projections by average variant.

Year	With HIV	Without HIV	Difference	% Difference
2001	1,028,600	1,028,600	0	0
2006	1,106,008	1,106,652	644	0.058
2011	1,177,693	1,179,662	1,969	0.167
2016	1,258,887	1,262,724	3,837	0.304
2021	1,337,469	1,344,029	6,560	0.488
2026	1,405,370	1,415,278	9,908	0.700
2031	1,456,834	1,470,976	14,142	0.961
2036	1,501,831	1,520,732	18,901	1.243
2041	1,541,046	1,566,101	25,055	1.600
2046	1,573,836	1,605,119	31,283	1.949
2051	1,588,899	1,626,993	38,094	2.341

Our average variant of the population projections of 2051 (1,589 million) are very close to projections prepared by Visaria and Visaria (1,581 million). The medium projections made by UN are also of the similar order (1,531). The high variant of our population projections (1,771 million) are also close to latest UN high variant projections of 2002 (1,870 million) as compared with their earlier projection (1,980 million) of 1995. These projections also indicate that for about two decades from now there is not going to be any respite in terms of the population growth rate. It is only after the second decade of this century that population growth is likely to show any retarding effect. In the first quarter of this century there is going to be the addition of about 430 million people as per high variant of the population projections whereas in the second quarter, the addition is going to be 313 million. In the low variant of population projections similar figures are 387 million and 211 million people.

Another important aspect of these projections is the likely effect of HIV/AIDS on the population projections. Dyson and Hanchate have used UN estimates of HIV/AIDS on mortality in terms of its reduction of life expectancy for 1997 to 2011-2016. Their estimates of population for 2026 with HIV/AIDS show a population of 1,394 million as compared to our low variant with HIV/AIDS of 1,405 million population. Part of the lowering effect on Dyson and Hanchate's projections is due to the initially lower estimate of 2001 which they have found as 1,010 million.

The projections also show the likely loss of precious life due to HIV/AIDS over the years. In the low variants of our estimate it is found that around 38 million people are going to die by 2051 due to disease, which is about 2.31 % of the total population. The number in the high variant of population estimates goes almost double and is found to be 65 million people amounting to 3.62 % of the total projected population.

Table 4. Population projections by high variant.

Year	With HIV	Without HIV	Difference	% Difference
2001	1,028,600	1,028,600	0	
2006	1,112,057	1,112,714	657	0.059
2011	1,191,169	1,193,207	2,038	0.171
2016	1,280,865	1,284,810	3,945	0.307
2021	1,368,920	1,375,742	6,822	0.496
2026	1,448,307	1,458,624	10,317	0.707
2031	1,513,509	1,528,231	14,722	0.963
2036	1,574,523	1,594,231	19,708	1.236
2041	1,631,509	1,657,805	26,296	1.586
2046	1,689,443	1,722,555	33,112	1.922
2051	1,706,209	1,771,241	65,032	3.672

Figure 1. Population projection by low variant 2001-2051.

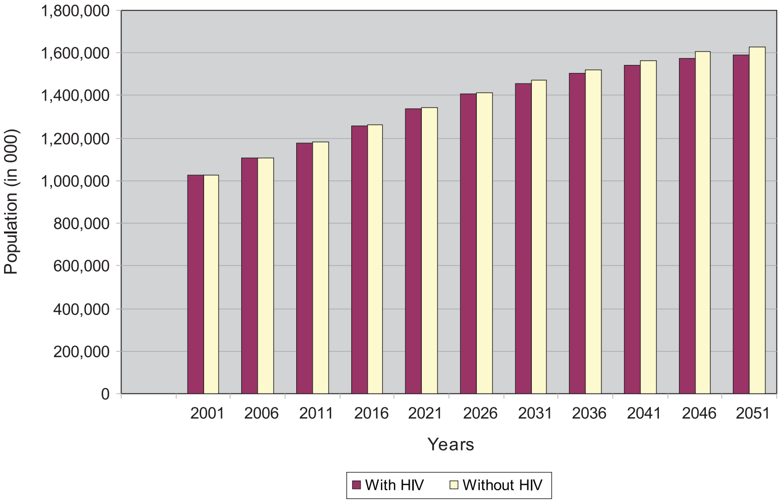
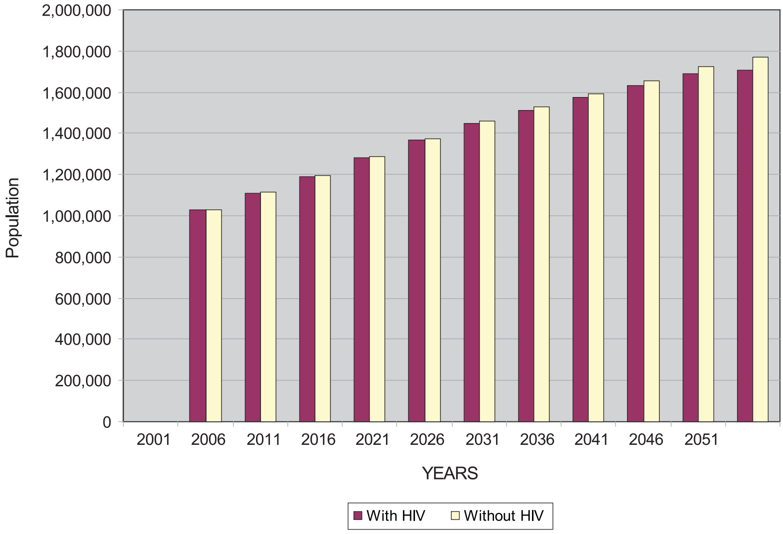


Figure 2. Population projection by high variant 2001-2051.



State wise Population Projections 2006 - 2051

Mortality

Regarding the state level projections of mortality, the figures projected by Population Foundation of India for 2001 were matched with the SRS figures and it was found that the figures differ with varying intensity and these were then adjusted accordingly. These projected values of longevity of life for each state are given in Annex Table 1.

Fertility

Regarding the state level projections of fertility, Population Foundation estimates of TFR for 2001 were matched with the SRS estimates and in the light of discrepancy the figures were adjusted. Although this procedure did not affect the figures in any big way, some important improvements were made. For example in Gujarat, TFR was found to be 2.9 instead of estimated 2.3. Similarly in Bihar the value of TFR given by SRS 4.4 was found to be much higher than estimated value of 3.9. Other states giving substantially higher SRS values than the estimated one are Punjab, Haryana, Tamil Nadu and West Bengal. In Karnataka, Maharashtra and Orissa, however, the SRS values were found to be marginally less than the estimated values. These projected values after modifications are given in Annex Table 2.

The two variants of population projections for major states are given in Annex Tables 3 and 4.

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Annex Table 1. Projected values of life expectancy 2006–2051, India and the major states.

STATE		2001	2006	2011	2016	2021	2026	2031	2036	2041	2046	2051
Andhra Pradesh	M	62	63	64.1	65.2	66.2	67.3	68.3	69.3	70.4	71.4	72.5
	F	64.6	65.9	67.1	68.4	69.7	70.9	72.2	73.5	74.8	76	77.3
Assam	M	57.7	57.7	62.7	62.7	66.7	66.7	68.7	68.7	70.7	70.7	72.7
	F	58.1	58.1	61.1	61.1	66	66	69.2	69.2	71.7	73.6	73.6
Bihar	M	61.4	63.4	65.4	66.3	68.4	68.9	70.4	71.2	71.9	72.7	73.3
	F	59.5	62.5	65.6	67.8	70	71.7	73.3	74.2	75	76.4	77.8
Gujarat	M	62.4	64.4	66.4	67.9	69.4	70.4	71.4	72.6	73.7	74.3	75
	F	64.4	66.8	69.2	71	72	74	75.2	76.3	77.4	78.2	79
Haryana	M	64.7	66.8	68.8	69.9	71.1	71.9	72.7	73.3	74	75	76
	F	65.4	67.1	68.8	70.2	71.6	72.4	73.2	75.4	77.7	77.1	77.1
Karnataka	M	62.8	64.3	65.8	67.3	68.8	69.2	69.5	70.3	71	71.8	72.5
	F	66.2	67.7	69.2	67.3	68.8	69.2	69.5	70.3	71	71.8	72.5
Kerala	M	70.8	71.8	72.8	73.7	74.6	75.3	75.9	76.6	77	77.7	78.2
	F	75.9	76	78	78.9	79.8	80.4	81.1	81.7	82.2	82.2	82.2
Maharashtra	M	65	66.6	68.1	69.3	70.5	71.5	72.5	73.4	74.3	75	75.8
	F	65	66.7	68.4	69.7	70.9	71.9	72.9	73.8	74.7	75.3	75.8
Madhya Pradesh	M	57	59	61	63	65	66.5	68	69.1	70.1	71.6	71.6
	F	56.7	59.3	61.8	63.3	64.8	66.6	68.3	69.6	70.9	71.9	73
Orissa	M	58.4	59.9	61.4	63.7	66	67.1	68.1	69.1	70	70.6	71.1
	F	58.4	59.9	61.4	63.7	66	66.8	68.1	68.9	70	70.6	71.1
Punjab	M	67.4	68.2	69	69.8	70.6	71.1	71.6	71.9	72.2	72.9	73.6
	F	69.5	70.7	71.8	72.8	73.8	74.6	75.4	76.1	76.8	77.3	77.8
Rajasthan	M	60.5	62.2	64.7	66	67.9	69	70.4	71.4	72.4	73.1	74.2
	F	61.6	64.1	66.6	68.7	70.8	72.3	73.7	74.9	76.1	77.1	78.1
Tamil Nadu	M	64.2	65.8	67.3	68.2	69	70	71	71.9	72.8	73.7	74.6
	F	66.3	68.4	70.6	72	73.4	74.7	75.9	76.9	77.9	78.7	77.9
Uttar Pradesh	M	59.4	63.9	65.6	67.3	68.6	69.9	71	72.1	72.4	72.9	73.8
	F	58.5	61.3	63.5	65.3	68.3	70.1	72.1	71	74.8	76.1	77
West Bengal	M	63.3	64.8	66.4	67.4	68.4	69.2	70	70.8	71.5	71.9	72.4
	F	64.8	67	69.3	70.1	72.6	73	75.1	76	77.2	78	79

Annex Table 2. Projected total fertility rates 2006 – 2051.

STATE	2001	2005	2011	2016	2021	2026	2031	2036	2041	2046	2051
Andhra Pradesh	2.3	1.95	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Assam	3	2.65	2.3	1.95	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Bihar	4.4	3.84	3.28	2.72	2.16	1.6	1.6	1.6	1.6	1.6	1.6
Gujarat	2.9	2.47	2.03	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Haryana	3.1	2.6	2.1	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Karnataka	2.4	2.2	2	1.8	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Kerala	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Maharashtra	2.4	2.2	2	1.8	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Madhya Pradesh	3.9	3.57	3.24	2.91	2.59	1.6	1.6	1.6	1.6	1.6	1.6
Orissa	2.7	2.42	2.15	1.88	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Punjab	2.4	2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Rajasthan	4	3.76	3.52	3.28	3.04	2.8	2.56	2.32	2.08	1.84	1.6
Tamil Nadu	2	1.8	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Uttar Pradesh	4.56	4.38	4.16	3.93	3.71	3.94	3.27	3.04	2.82	2.6	2.6
West Bengal	2.4	2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6

Annex Table 3. Population projection of major states of India 2006-2051—average variant.

State	2001	2011	2021	2031	2041	2051
Andhra	76,209,000	82,737,600	87,485,896	89,700,104	89,153,800	86,659,896
Assam	26,655,000	29,943,400	32,616,000	34,159,800	34,776,600	34,403,300
Bihar	82,999,000	99,473,800	115,984,000	125,760,000	133,386,000	137,740,000
Chattisgarh	20,834,000	25,300,200	29,068,700	31,200,400	32,942,102	33,740,000
Gujrat	50,596,992	57,241,500	61,244,900	64,116,800	65,138,000	64,064,000
Haryan	21,145,000	24,105,300	26,136,200	27,597,300	28,298,200	27,993,500
Jharkhand	26,946,000	31,890,100	34,897,700	37,422,000	38,829,900	39,012,300
Karnataka	52,851,000	58,766,700	63,319,100	65,491,300	65,989,704	64,524,500
Kerala	31,842,000	34,554,800	36,348,400	37,284,000	37,078,800	35,747,000
Maharashtra	96,879,000	106,638,000	114,336,000	118,404,000	119,423,000	116,786,000
MP	60,348,000	70,850,600	82,203,400	90,738,704	95,479,504	98,350,600
Orissa	36,805,000	40,437,300	43,207,900	44,513,800	44,744,700	43,579,800
Punjab	24,359,000	26,617,100	28,221,400	29,056,300	28,945,000	27,973,500
Rajasthan	56,507,000	66,788,500	80,096,104	94,075,000	106,136,000	114,619,000
Tamil Nadu	62,406,000	67,117,400	69,934,104	70,962,296	70,091,400	67,458,200
UP	166,198,000	205,184,992	255,864,000	310,872,000	368,574,016	424,812,000
Uttranchal	8,489,000	10,698,600	13,222,700	15,947,600	18,971,900	21,880,200
WB	80,176,000	88,136,848	94,565,584	97,759,616	97,642,960	95,154,536

Annex Table 4;. Population projection of major states of India 2006-2051—higher variant.

State	2001	2011	2021	2031	2041	2051
Andhra	76,209,000	83,381,800	88,861,200	91,911,600	92,385,800	90,990,896
Assam	26,655,000	30,315,692	33,457,188	35,585,324	36,916,004	37,318,856
Bihar	82,999,000	100,764,848	119,038,408	131,444,408	142,443,840	150,618,016
Chattisgarh	20,834,000	25,551,640	29,638,514	32,243,500	34,601,172	36,067,468
Gujarat	50,675,000	57,604,140	62,542,564	65,961,648	67,812,744	67,621,648
Haryana	21,145,000	24,347,200	26,626,700	28,341,700	29,312,300	29,228,800
Jharkhand	26,946,000	32,710,262	37,945,776	40,919,108	43,354,968	44,567,964
Karnataka	52,851,000	58,810,880	63,414,208	65,646,460	66,219,736	64,832,272
Kerala	31,842,000	34,583,532	36,404,484	37,374,024	37,210,156	35,920,696
Maharashtra	96,879,000	107,565,424	116,341,336	121,709,232	124,352,416	123,437,376
MP	60,348,000	71,269,416	83,168,080	92,512,144	98,289,560	102,352,304
Orissa	36,805,000	40,784,972	43,966,512	45,768,072	46,611,448	46,088,096
Punjab	24,359,000	26,851,400	28,725,800	29,871,900	30,150,200	29,590,300
Rajasthan	56,507,000	67,556,152	81,877,408	97,572,912	112,046,720	123,422,696
Tamil Nadu	62,406,000	67,661,608	71,014,936	72,696,192	72,632,968	70,837,152
UP	166,198,000	205,433,184	256,413,504	311,939,552	370,433,280	427,699,296
WB	80,176,000	88,958,904	96,362,848	100,684,176	101,944,528	100,947,384
Uttranchal	8,489,000	10,712,463	13,252,588	16,004,695	19,070,500	22,033,028

The ‘Tipping Point’ in Indian Agriculture: Understanding the Withdrawal of Indian Rural Youth

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> *“We are all, at heart, gradualists, our expectations set by the steady passage of time. But the world of tipping point is a place where the unexpected becomes expected, where radical change is more than a possibility. It is contrary to all our expectations a certainty.”*
>
> -Malcolm Gladwell, Tipping Point

Introduction

A number of recent occurrences suggest that India might very well be at the ‘tipping point’ of the (de)growth in its agricultural population and with growing urbanization, better literacy standards and greater skill attainment by rural youth it might take a steep turn downwards thus changing the nature of farming in the country drastically.

At times the ‘gradualist’ in us tells that it’s probably too early and too ambitious to make such assertions – more than 50 % of the population is currently engaged in farming; the rate of growth of nonfarm jobs is abysmal, the services sector has too little job opportunities to offer and the manufacturing sector has only been experiencing jobless growth. The transition, even if it were to happen, will take a long time. However, if one took cognizance of the surroundings and the developments therein, there are a sufficient number of reasons for us to think to the contrary. First, the farming population in several parts of India registered a decline in absolute terms for the first time in 2001 with states such as Tamil Nadu and Kerala at the forefront (Economist 2001). Notably, the rural male cultivator population has declined by 2.8 million between 1991 and 2001 (a decline of 3.6 %) changing the male-female cultivator ratio from 80:20 in 1991 to 67:33 in 2001. These are significant developments, given the impact of dropping populations have on the nature of farming practiced in an economy[1]. Second, the

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[1] Bicanic (1972 cited by Griggs 1982) classified countries on the basis of rate of growth of their agricultural populations as relative and absolute and identified how fall in agricultural population caused significant reorganization of farming, the most drastic changes coming when the population fell in absolute numbers - peasants move from maximizing output per unit of land to maximizing output per head (as there are more number of people to feed per farmer); farm size becomes larger and the agricultural populace is dominated by large farmers; there is acute labor shortage as young and able bodied men withdraw driving mechanization, and finally as the gap between farm and nonfarm incomes widen governments intervene to restore parity.

growth performance of the Indian economy gives sufficient grounds to expect a significant change in the employment scenario[2]. The 6th economic census which reports that the growth in labor opportunities in the nonfarm sector is outpacing the growth in labor force gives further hope. Third, the current farm crisis in the country seems to be another dominant force causing many to quit out of desperation. The mounting number of farmer suicides and the rising disenchantment with the profession among farmers (NSSO 2005) are some subtle but disturbing indicators. Further, if we look back in time we find that in most cases withdrawal from farming took place in a very short concentrated period of time either because of growth in the nonfarm sector or farm crisis as experienced by US in 1980s. Most of the East Asian economies such as Japan, South Korea, and Taiwan which are similar to India in being land scarce and labor surplus underwent steep fall in agricultural population within a short span of less than 20 years. To support the argument further, most of them were experiencing similar economic growth rates (that India is experiencing now). Last but definitely not the least, the talks of efflux of youth from farming is increasingly gaining weight among the premier Indian academic circles. The noted agricultural scientist, Dr M S Swaminathan, pointed out recently that in the coming years one of the biggest challenges for Indian agriculture would be to retain its youth in agriculture and unless farming became both ‘intellectually stimulating and economically rewarding’ it would be difficult to attract or retain rural youth in farming (Swaminathan 2001).

Place of This Study in the Strategic Analyses of India’s River Inter-inking Program

The river-linking proposal claims to address the water needs of India in 2050 and beyond. For that to happen it is important to understand what shape Indian agriculture (as it is the largest user of water) would take in 2050. Human capital, being one of the most important factors driving changes in structure of agriculture (Boelhje 1992; Bicanic 1972 cited by Griggs 1982), a look at the withdrawal of Indian farmer population and its drivers becomes crucial to the analysis of the proposal. It is in this regard that the paper takes an intensive look at the landed rural youth of India across 14 locations in 12 states and their association with farming, and finally tries to identify (with the help of logit models) the factors fuelling the process of their withdrawal from agriculture.[3] In order to place the phenomenon in its larger context, we also review some international literature on withdrawal of farmers from agriculture.

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[2] Bhalla and Hazell 2003 in their paper on employment growth in India had projected that with an overall economic growth rate of 9 % and with an employment elasticity of 0.1, employment in India will match the labor force by 2010 and if the employment elasticity was taken to be higher the country will reach full employment by 2004!....and by 2020 will have an excess of 68.4 jobs.

[3] The rationale for focusing on landed rural youth is similar to ‘prosumer’ analysis that market researchers do. ‘Prosumers’ are the trendsetters for any particular product category. Their usage and involvement with the product defines how the product would evolve in future. Market researchers have been thus tracing the behavior of these consumers to fine tune their products. For Indian agriculture, landed youth are the ‘prosumers’ as they would define how Indian agriculture would evolve in future.

Why Farmers Quit – Existing Wisdom

Why do farmers quit or what makes farmers quit farming en masse, the occupation they have been in all their lives? The theory of farm exit and a related yet more widely known concept - the 'farm problem' has been an issue of keen interest to scholars since a long time. Unfortunately, most of the contribution to the literature has come from work done on US farms, posing limitations to its applicability to other economies such as India. However, we believe that much of the understanding (by virtue of the basic nature of farm sector) would hold for all type of economies. In this section we put together some of the work done on answering the question –"why farmers quit?" and assemble the major hypotheses and debates in the field to serve as a foreground to our study and analyses.

The Farm Problem

There is no agreement among scholars on what exactly constitutes the 'farm problem', though a significant amount of work has been done on the issue (Gardner 1992). The nature of the problem has also been changing over time with increasing heterogeneity of the farmer population (Offutt 2000). Broadly, the term can be taken to mean economic difficulties faced by farmers as a result of low farm incomes (vis-à-vis nonfarm) and large instability and variability in the income from farming. The common response of farmers to the problem is to migrate to urban areas or to nonfarm occupations which provide higher returns to per unit of labor applied. The question that arises is - what explains the difference in farm and nonfarm incomes? Gardner 1992 attributed the difference to the factor market conditions. Johnson 1959 (Gardner 1992) also wrote that the farm problem was "as a result of the employment of more labor in agriculture than can earn as large a real income as the same labor could earn elsewhere in the economy." Further, one of the many ironies of the sector is that most of the times the aforesaid 'farm problem' arises out of success of farming itself.

> *"The greater the increase in farm productivity, the greater the imbalance between supply and demand of farm products which has to be corrected by an outflow of labor or by lower farm prices. Unless the outflow of labor from farming is fast enough, an increase in farm productivity leads only to lower farm prices and lower farm incomes."*
>
> (Houthakker 1967 cited by Gardner 1992)

Thus the incentives for a farmer to farm go on declining even with a good performance and many a time there is no option but to quit. Offutt 2000 in her paper on "Can the farm problem be solved?" puts it very well – "there is and always will be money to be made in farming but the question is by how many?"

Why Farmers Quit

As rational actors, while making a decision to quit farming, farmers compare the utility they derive from farming vis-à-vis that derived from quitting and taking up full-time nonfarm employment. The theory of farm exit and most of the studies done on the subject essentially rest on this assumption. Transaction costs involved in making a shift (including relocation) is also an important determinant (Goetz and Debertin 2001). Lower the costs, higher the propensity to shift. Goetz and Debertin 2001 in a cross-county analysis of US farms conclude that in case of counties facing a net loss of farm operators, lower transaction costs led to faster rate of withdrawal from farming. These costs/utilities are either aggravated or lowered by various factors. Scholars have gone into significant depth exploring the impact of these factors which can be classified into three types - farmer associated (such as education and skill level of farmers, involvement in nonfarm activities, family size); farm-specific (size of farm, value of production) and nonfarm (such as proximity to metropolitan areas, overall GDP of the region, government interventions etc.).

Glauben et al. (2003) notes that at a broad level, farmer withdrawal studies can be classified into two types - the first type is empirical studies at the farm household level while the second type focuses on adjustment of farm labor at aggregate (sector/regional) level. While the first type help bring in more household and farm specific characters in the analyses, the second type help capture the macro-economic forces and the influence of government policies on changes in labor allocation in the farm sector. Authors have tested the impact of several farm/ nonfarm, household/ regional level variables on the decision of farmers and have found both similar and divergent results. We shall first take a look at the points of dissent.

One of the most popular debates in the field is on the question whether a prior involvement in nonfarm occupation reduces or increases the chances of withdrawal from farming? A large number of farmers in developed economies today practice farming as a part-time activity. The trend is becoming increasingly in vogue and does not give conclusive evidence on whether part-time farming sets them on their way out of agriculture. Authors like Kimhi and Bollman 1999, Kimhi 2000, Goetz and Demertin 2001 in their studies on Canadian, Israeli and US farmers, respectively, conclude that nonfarm income has a stabilizing impact on the farmer’s household economy. Farmers in these cases use their nonfarm income to augment their farm activities and it thus serves as a stabilizing factor rather than an avenue for exit. On the contrary, authors such as Pfeffer 1989 and Weiss 1999, see a strong link between nonfarm employment and withdrawal from agriculture. That is, growth in nonfarm employment causes people to move away from farming by providing the much needed outlet. They propose that an exposure to nonfarm occupation lowers the transaction costs (Glauben et al. 2003 have also called ‘the beaten path’ effect) involved in the shift making the exit decision easier.

Another point of deviation has been on the impact of government intervention and macro-economic environment. A comprehensive study done in the OECD countries (1994) concluded that farm family labor as well as hired labor is not particularly sensitive to business cycle conditions or to agricultural prices. However, Andermann and Schmidt (1995, cited by Glauben 2003) in a study on Germany have found the labor significantly responsive to macro-economic changes and agricultural prices. Government payments too have been found to have a contrasting impact. On the one hand, while income assistance in terms of price supports results in slow down of migration; on the other land diversions lead to greater migration out of farming (Barkley 1990).

Among the farm specific characteristics, it is found that an increase in average farm-size significantly reduces the tendency to close down farms (Pietola 2002; Glauben et al. 2003; Goetz and Debertin 2001). The justification being that large farm sizes make farming much more economically viable for the farmers by enabling them to reap economies of scale and bring in use better and cost-effective technologies. There are, however, evidences to the contrary. For example, Speare 1974 in case of Taiwan found that the large landholders showed a greater tendency to withdraw. This was by virtue of their being able to gain good quality education and to move to better occupations. Large farmers could also take greater risks compared to the small and venture out more in search of greener pastures.

Most of the authors with exceptions such as Zhao 1999 have found that higher education and greater number of skills lead to greater propensity to migrate. Weiss 1999 found several other farmer associated characteristics to be playing a role such as gender, age, family size, succession information and attitude towards risk. Among these the trend in age has lately been a cause of worry among the developed countries. A number of policymakers and academicians have been expressing serious concerns over the 'graying of farm sector' because of (1) increased exit and (2) dropping of rates of entry into farming by the rural youth (Gale 2002). What roles do these factors –age, land size, education and skillfulness etc., play in the context of Indian farmers? We shall try and address this question in the later sections.

The Case of Labor Surplus Economies

As mentioned earlier, one of the lacunae in the literature on the theory of farm exit is that not much work has been done on labor surplus economies. This could possibly be because of their very definition- labor surplus and thus not requiring much attention on this aspect. However, there is a serious flaw in this line of thinking. Zhou 2004 critiques the work of Schultz challenging one of his assertions that low income countries saddled with traditional agriculture do not suffer from the problem of many farmers leaving agriculture for nonfarm jobs. He says that many low income countries especially from 1950 onwards have been increasingly open to high income economy… "small peasants migrate to those rural areas which have entered the high wage stage, cities and abroad to earn higher income as part-time and absent farmers, thus are up against the problem of adapting the agricultural sector to a high income country"(Zhou 2004). The changes in post World War II Japan, where the full-time farming households declined from 50 % in 1950 to 20.5 % in 1965 is a case in point (ibid) which proves that how even a labor surplus economy could undergo a steep fall in its agricultural labor force in a short period of time and defy existing wisdom.

In most of the East Asian economies, however, mass withdrawal of population from agriculture was largely a post - World War II phenomenon (Ohkawa 1961) thus, bringing into play a very different set of factors. There was also a great emphasis on industrialization and concentrated efforts were made to channelize resources, including human capital, to fuel the industry-led growth of the economy. China started experiencing mass rural-urban migration of labor during the 80s. However, much of this was the floating population. Rarely, migrants settled (or could afford to settle) in cities. Part-time farming became a popular arrangement where farmers spent most of their productive time in rural nonfarm or urban activities. In peak agricultural seasons they came back to their farms only to leave again (Zhao 1999). In India too, this has become increasingly in vogue in a large number of regions (Sharma, forthcoming). How this part-time arrangement affects farming, however, is a less understood phenomenon and needs to be studied.

In economies such as India, the ‘farm problem’ is probably worsened by virtue of its labor surplus nature. Dantwala and Donde 1949 wrote about the ‘uneconomic cultivators’ of India way back in the 1950s saying that the problem with Indian agriculture was not so much of uneconomic cultivation but of ‘uneconomic cultivators’ and it was this group of farmers that needed maximum policy attention. In a study of 11 villages in the then Bombay province, the authors found that 71 % of the cultivators came in the category of ‘uneconomic cultivators’ who continue to till land without necessary resources, living a life of insecurity and sub-marginal existence. For the 70 % of land that was cultivated as economic units, the roadblock to efficient production was fragmentation of landholdings. The authors observed that the number of fragments operated grew with the size of cultivated holding of a farmer thus “what seemed to have been gained in the size was lost in the number of fragments that comprised the unit of cultivation” (past tense added) (ibid). There was widespread leasing in and out of land to make farming units viable but taking all that into account, still, only 27 % of the cultivators operated 55 % of the land. According to the authors’ estimates 50 % of the cultivator population in the region was redundant! (ibid). There were suggestions made to redistribute land - transfer from those holding more than economically viable holdings to the uneconomic cultivators. Rural industrialization was also proposed as an effective medium to promote diversification of livelihoods thus reducing the pressure on land. Unfortunately, none of the policies could be implemented effectively and the uneconomic mode of cultivation continued ruining the economics of cultivation in the subcontinent even further. Bhalla and Hazell 2003 observe that with 60 % of the labor force producing around a quarter of the GDP, the relative productivity of workers in agriculture is less than one-fourth of the nonagricultural occupations. In recent times several macro-economic changes and farm level changes have worsened the agricultural employment scenario. For example, in the post-liberalization period the employment growth in agriculture dropped from 1.49 % pa to 0.01 % pa (Bhalla and Hazell 2003). The recent trend of the over-capitalization of agriculture also influenced the employment elasticity of agriculture adversely. The employment elasticity of agriculture is approaching zero (0.01 in the post-reform period, Planning Commission report cited in Bhalla and Hazell 2003) and has been reported to be negative in some states such as AP (-0.13), Kerala (-0.92) and UP (-0.13).

Given this, much of the pessimism about the status of employment in Indian agriculture is justified. We, however, aim to add another leaf to the discussion by arguing that the drop in employment in agriculture cannot be solely attributed to the happenings on the agricultural front. There are developments on the nonfarm side which are having significant and some times greater impact.[4] At present much of the deliberation on the withdrawal of Indian farmers seems to be pre-occupied with declaring it to be a distress phenomenon. We believe that the reality is much more complex. Indian villages are undergoing a major transformation causing perceptible changes in aspirations of the rural mass, especially the youth who are now opting out of farming. Some of these aspects have been dealt in greater detail in another of our papers (Sharma, forthcoming). The participation rates of the 5-14 and 15-29 age groups are declining

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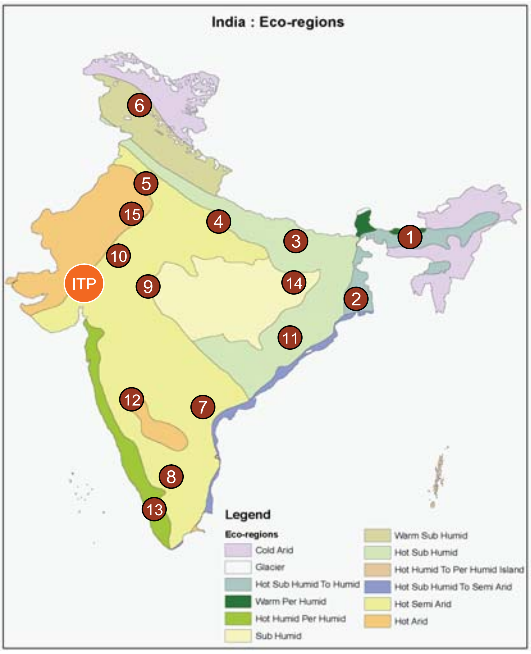
[4] Bhalla and Hazell 2003 hypothesize that growth in secondary and tertiary sectors has a major contribution in the decline in farmer population. There has been a notable increase in labor productivity and wages in agriculture and the wages in nonagricultural sector are now significantly higher than in agriculture. This suggests that the shift from agriculture to nonagriculture is not a distress phenomenon.

as more young people stay in education (Bhalla and Hazell 2003). There is increased migration from rural to urban areas (NSSO 2003). Urbanization is also growing apace casting great influence on the suburbs and the villages in the vicinity. How these factors contribute, however, is not fully understood. In this paper we make an attempt to identify some of the factors contributing to the withdrawal of the rural youth from farming.

Data and Preliminary Observations

The data used in the study was collected through a primary survey of the rural youth across 14 locations[5] covering 13 states of India- Kashmir, Haryana, central Uttar Pradesh, lower Assam, Jharkhand, central Orissa, north Bihar, West Bengal, Gujarat, Rajasthan (2 locations), Madhya Pradesh, north Karnataka, and coastal Andhra Pradesh (Figure 1). Data was collected on their education and skill-level, their asset-holding, social group, their association with agriculture, their perception about farming as a career alternative and their plans for future with regard to a shift to nonfarm occupation. These plans have been made the basis of our analysis. We understand that the plans to withdraw might not convert into actual withdrawal but with the

Figure 1. Study locations.



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[5] A location in this context means a block of contiguous districts which have relatively similar agro-climatic and hydrological features. The locations were selected so as to represent a reasonable hydro-geographic diversity of the country.

question – 'Do you have immediate plans to shift to another occupation'? Further supported by the mention of the job they were considering to take up, we expect to paint a reasonable picture of the withdrawal phenomenon.

We also collected data on irrigation availability and proximity to the nearest urban centre. At the beginning of the study, some pilot survey results revealed that the nature of the involvement of the youth in farming varied with respect to the degree of their association with the day to day management of the farm. Based on this, we classified the respondents into full-time and part-time farmers and those with no-involvement in farming.[6]

A significant proportion of the rural youth were found to be practicing part-time farming (35 %). The phenomenon was more pronounced in villages close to town rather than those away from town (40 % vis-à-vis 29 %). We also found a significant correlation between the degree of association with farming and per capita value of agricultural production (0.62). Lower the value of agricultural production per capita, higher the number of part time farmers/no-involvement farmers.

About 35 % of the youth migrated for work outside their villages and most of this migration was seasonal. A large number of youth (30 %) commuted to nearby towns/villages. Most of them worked as agricultural labor, construction workers and contractual workers at agricultural produce markets (*mandis*), factories, bus stops and railway stations. These jobs were low-paying and irregular in nature.

Most of the people interviewed had education up to secondary level (37 %), followed by primary education (32 %). 16 % of the youth interviewed were illiterate and a negligible 1 % had professional education from technical training institutions such as Industrial Training Institutes (ITIs). A very small number of youth (24 %) possessed some kind of nonfarm skills, reflecting the poor skill-set of India's rural youth. This prevented them from gaining entry into remunerative occupations. The most common skills found among the youth were driving, electrical and mechanical repair work, and masonry. A small percentage possessed knowledge in computer applications as reported.

There was a visible sign of aging of the farmer population. Along with the details of the youth being interviewed we also took some relevant family details. The average age of a person farming was found to be 36 (for an effective sample of 8,500 plus in the working age group). Among the youth, also there was a difference in age of the part-time and the full-involvement farmers (Figure 2). Though the mean age is not much different, it shows that the proportion of full-time farmers is relatively skewed towards the higher age group.

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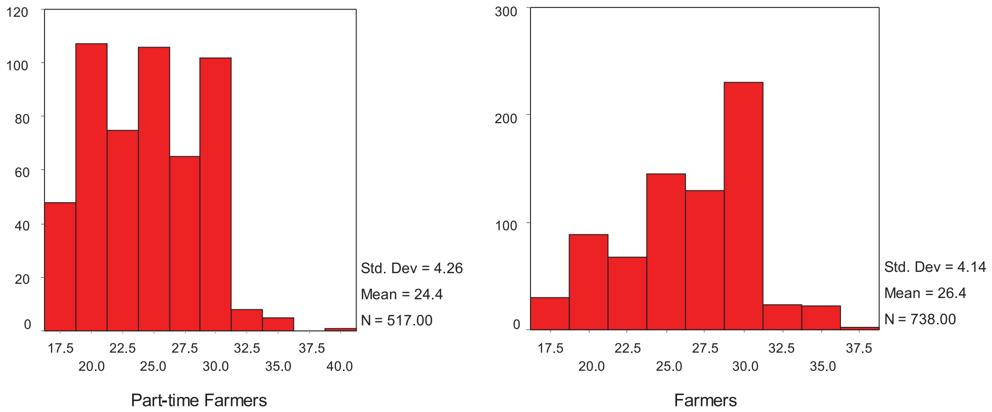
[6] The classification was done based on the following criteria. The 'high involvement' category included the youth who were actively involved in management and supervision of their farms. One can term it 'full-time farming'. The 'medium involvement' category included the youth who contributed labor on their farms when they were free from their main activity. One can term it 'part-time farming'. The 'no involvement' category included youth who had almost no involvement in the management of their farms.

Figure 2. Age distribution of part time and high involvement farmers.



Source: Primary Survey, 2005

Another interesting phenomenon we observed on the field was that both the small and large farmers were on their way out. Reverse tenancy has been talked about much where small and marginal farmers, because of the nonviability of their small parcels of land are handing it to large or middle farmers. Recent studies of Jodhka 2006 also shed light on this phenomenon in Punjab agriculture where he says that the phenomenon of withdrawal is much stronger in small and marginal farmers. However, in our field work we saw several instances of large farmers fallowing their land and moving out of rural life.

Finally, one of the key questions we wanted to look into was the impact of irrigation on withdrawal behavior. It is generally believed that irrigation has a significant impact on employment generation. Thus, if the national river interlinking program was to get functional and provide irrigation to newer areas it should ideally contribute to reducing rural-urban migration by generating employment. We shall test for all these hypotheses by using some occupational choice models in the next section.

Occupational Choice Models

Based on these preliminary observations we postulate that a farmer, characterized by his age, skill level, education, landholding size, irrigation facilities and location of his farmland, seeks to maximize his welfare by making a choice regarding his present agricultural occupation. In this section, using a suitable regression model we attempt to address the question why youth are planning to shift to other nonagricultural activities, and assess the odds of an average rural youth moving out of agriculture.

Here the behavioural response of the youth involves a discrete binary choice of either shifting to other nonagricultural activities or staying in agriculture. We consider the farmer’s willingness to shift as a dependent variable and code it as 1 for his plan to shift to nonagricultural activities and 0 for otherwise. The independent variables explaining the dependent variable include skills (S), education (E), age of the farmers (A), land holding size of the farm (AVL) and irrigation (I). The variables are described in more detail in Table 1.

Methodology and Estimation

When the dependent variable is binary, application of the linear regression model is more complex as the dependent variables can only take values of 0 and 1. However, from knowledge of relevant independent variables, what we want to predict is not a precise numerical value of a dependent variable, but rather the probability (*p*) that that a farmer will move out of agriculture is 1 rather than 0. But there are problems in using the probability as the dependant variable in an ordinary regression as numerical regressors such as average land holding may be unlimited in range. If we expressed *p* as a linear function of skills, education, and average landholding size and so on, we might then find ourselves predicting that *p* is greater than 1 (which cannot be true, as probabilities can only take values between 0 and 1).

To overcome such complexities, we use a logit framework, where the dependent variable represents the log of the odds ratio of farmer's plan to shift out of agriculture. The odd is defined here as the ratio of probability that farmers will make a choice to shift out of agriculture to that he remains in agriculture. As the number of farmers in the sample is 900 and 555 farmers are planning to shift out of agriculture, the probability (p) that a farmer is willing to move out of agriculture can be computed as:

$$p = \frac{555}{900} = 0.62$$

The probability that a farmer is willing to remain in agriculture is $1 - p = 0.38$. Given p, the odd ratio (O) can be derived as;

$$O = \frac{p}{1-p} = \frac{0.6}{0.4} = 1.5$$

it means if two farmers choose to remain in agriculture, then three farmers would be willing to move out of agriculture. The logit model estimates the natural logarithm of such odd ratio, O that involves fitting to the data an equation of the following form:

$$LOGIT\left(\frac{p}{1-p}\right) = \alpha_0 + \alpha_1 (S) + \alpha_2 (E) + \alpha_4 (I) + \alpha_5 (A) + \alpha_6 (AVL)^2 \qquad (1)$$

where p = probability (p) of a farmer willing to move out of agriculture, and

$$O = \frac{p}{1-p}$$

represents the odd ratio of farmers moving out of agriculture. Table 1 presents the regression results.

The regression results show the effects of different factors that influence the farmer's decision to shift. As per the results, the odd of moving out of agriculture is 1.50 for the farmers who possess nonfarm skills. Possession of skills increases the marketability of a person. The returns to migration are much higher if a person possessed certain skills. In Gujarat, we have observed that there was a huge differential between the wages received by a trained mason and other regular laborers. The mason would earn to the tune of Rs. 150-200 per day while the rest could only earn up to Rs.75-80. Further, while skills increase the odds of migrating, migration and the exposure thereof also lead to attainment of skills by the youth. Part-time farmers all-over were found to possess greater number of skills.

Table 1. Estimated regression results.

Variables	Coefficient	Odd ratio	Z	P>z	Definition of variable
Skills	0.41	1.50	2.21	0.03	S=1 if the person possesses skills, =0 otherwise
Education	0.34	1.40	1.91	0.06	E=1 if the person is educated, 0=otherwise
Irrigation	0.23	1.26	1.47	0.14	I=1, if irrigated region, 0=otherwise
Land holding	- 0.23	0.79	-3.25	0.00	AVL=Average landholding
Landholding -square	0.01	1.01	2.47	0.01	
Age	0.50	1.64	3.33	0.00	A=1 if age less than 30 years, 0=otherwise
Constant	-0.09	0.92	-0.39	0.70	
Number of observations		892			
Log likelihood		-574.5			
LRchi^2 (6)		34.5			
Prob > chi^2		0			

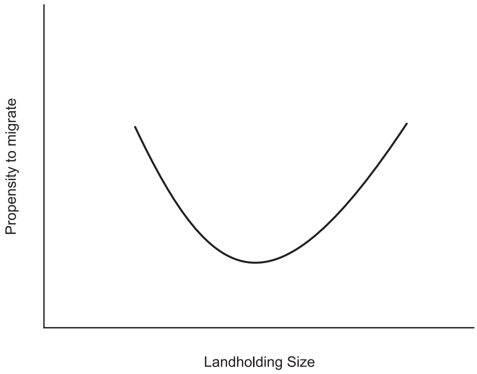
Similarly, education has a positive effect on the farmer’s propensity to shift out of agriculture. The odd ratio of moving out of agriculture is 1.40 for education. The results, however, are not significant at 5 % level. The possible explanation could be the inability of other sectors to absorb rural youth. For a large number of educated youth in the countryside, higher education does not immediately translate into employment (Ghosh et al. 2006). In our sample, youth with vocational education are significantly low in percentage, but that too has not been found to increase employability by any significant degree (Ghosh et al. 2006).

Age too is an important factor. The odd ratio in favor of shifting out of agriculture is high among farmers of age less than 30 years. The possible explanation of this could be that younger farmers are more open to opportunities, can take the risks of moving out and experimenting with newer jobs and unfamiliar surroundings. They also command higher wages because of their faster learning ability and greater adaptability. In case of some US farms, Gale 2002 found that occupational mobility was generally higher among younger farmers and they were more sensitive to farm nonfarm earning differentials, farm prices, and interest rates compared with the old farmers. Another explanation of the graying of the farm sector could be what Molho 1995 calls ‘cumulative inertia’ whereby individuals form attachments to area, friends, jobs etc, which grow over time. The cumulative inertia in older farmers would be higher reducing the propensity to migrate.

Results show that lower average size of land holdings is one of the most important factors explaining the farmer’s higher propensity to migrate for other nonagricultural activities. This corroborates the widely held understanding on how small farm size pushes people out of farming. Year after year, the land holding is reducing, due to the division of property or, in many cases, accessions by the private usurers against loans. Farmers are finding it untenable to farm lower holding size land, and the sale of land and migration to urban areas has become rampant (Jayati Ghosh 2003). In some cases, farmers also migrate to repay their loans leaving the responsibility of agriculture on other members of the family.

In the field, however, we observed that alongside this distress phenomenon was another reality where large farmers too were making their way out of farming. To check for this we introduced another variable ‘landholding-square’. The positive coefficient of the square of the average landholding size in the quadratic relationship suggests a strictly convex or U shaped (Figure 3) relationship between farmer’s willingness to move out of agriculture and average land holding size.

Figure 3.



Policymakers often cite that irrigation is one of the key factors that may reduce the propensity to migrate. Our results, however, indicate an insignificant role of irrigation relative to other factors in influencing farmer’s decision to shift to other activities.

Finally, many policymakers argue that in the villages close to town, farmers are more likely to shift out of agriculture (Lucas 2000). It is an illustration of the bandwagon effect. People are attracted towards the better standard of living and the facilities available in towns. Also there is no dearth of literature suggesting why longer distance migrations may be less common. In a survey of migration in the developed countries, Greenwood 1997 identifies that moves over longer distances impose higher costs of foregone, intervening opportunities. Although in the Indian context much of migration is intra district and the internal travel cost is not too high, the general proposition that distance deters migration, seems to be consistent (Lucas 2000). For farmers far away from urban centers alternate occupational opportunities are also limited. Distance does not allow him to operate as a part-time farmer i.e., be partially involved in agriculture and work in town during the lull periods in agriculture. Our sample data also suggests strong positive correlation between distance and full time involvement of farmers in agriculture, which means that a farmer located far away from a town is more likely to be fully employed in agriculture. What factors would be driving migration from such areas then? We expect that factors affecting farmers’ willingness to shift out of agriculture would be stronger in terms of the odd ratio and statistical significance if he is far away from the town. We attempt to test our hypothesis by restricting the sample only to the case where the distance of the farms from the nearest town is above 14km. The distance of 14 km as a point of reference is taken based on the median value of the sample distance. Table 2 presents the regression results.

Table 2. Estimation results for sample >14 km away from urban centers.

Variables	Coefficient	Odd ratio	Z	P>z	Definition of variable
Skills	0.83	2.30	2.75	0.01	S=1 if the person possesses skills, = 0 otherwise
Education	0.86	2.37	3.46	0.00	E=1 if the person is educated, 0=otherwise
Irrigation	-0.38	0.69	-1.58	0.10	I=1, if the region is irrigated, 0 = otherwise
Land holding	- 0.23	0.79	-2.58	0.01	AVL=Average landholding
Landholding - square	0.01	1.01	2.03	0.04	
Age	0.58	1.79	2.70	0.01	A=1 if age is less than 30 years, 0=otherwise
Constant	-0.03	0.97	-0.10	0.92	
Number of observations		456			
Log likelihood		-277.9			
LRchi^2 (6)		39.8			
Prob > chi^2		0			

Comparing tables 1 and 2, we find that all the factors explaining the farmer’s willingness to shift out of agriculture are far more significant if the farmer is located at least 14 km away from a town. Striking is the improvement in the significance of the factors like skill and education. This implies that being skilled and educated becomes an important precondition. It is important to justify a drastic step such as leaving agriculture and working in some far away place. Our fieldwork shows that the unskilled category of youth could only get low-paying jobs such as loading-unloading of goods which did not fetch enough to sustain them in cities. In villages located far away from urban areas we find many cases of reverse migration where a number of youths had come back to the farm after some time because they were not able to sustain themselves in towns on the meager salaries they earned. Further, contrary to the results presented earlier, lack of irrigation, here has a positive impact on farmer’s willingness to migrate, and was significant at 10 % level. This implies that the distance from urban centers accentuate the negative impacts of water scarcity rendering out-migration from farming as the only option available to distressed farmers.

To conclude, five important points emerge from the analysis. Possession of skill seems to be an important factor in determining out-migration from agriculture. The odds of a farmer moving out of farming increase with skill attainment. Education too lends a positive push to migration but is not significant at 5 % level. Most of the out-migration is visible in the lower age group making age another critical variable. Among the farm level factors, farm size has an impact but the relationship manifests itself differently in the smallholder group and among the large farmers. Both appear to be withdrawing but for different reasons. Irrigation has no significant impact on the withdrawal behavior. Finally, proximity to towns is found to be a critical determinant fuelling out-migration decisions of farmers.

Policy Implications

What would be the face of Indian agriculture say 20-30 years hence? This paper is a deliberate attempt to add a new dimension to the present discourse which presupposes the persistence of overpopulated workforce in agriculture. We propose that the livelihood decisions of the rural youth would be the key to the future of Indian agriculture and there is a need to understand the various processes affecting it fully. This paper attempts to identify some of those and tries to check/validate some widely held notions through the use of statistical models. We, however, accept that the model is far from comprehensive. The blame may go little on the primary nature of the data which makes analysis difficult and more on our inability to quantify certain imponderables such as the changing aspirations of the rural youth and its impact on withdrawal.

Based on the present analysis, two kinds of implications, however, emerge – one for the short term and the other aimed towards long term changes in policies and institutions. In the short term we need to recognize that the current withdrawal from agriculture by the youth is not only inevitable but it is, to some extent, good for the economy. It would reduce the burden on agriculture and raise effective income for the residual population. But the situation as of now is troubling. The study shows that while a large mass of youth is trying to make its way out of farming few have the necessary skills to be able to move out of farming profitably. The result is poor quality migration, creating problems for urban habitations while not necessarily reducing the burden on rural areas. In the short term, skill building of the rural youth could be treated as a priority area. This would not only increase the pay-off to migration but facilitate withdrawal from farming as well.

Further, in the face of the withdrawal of the youth from farming we expect drastic changes in the agricultural demography. The low quality migration suggests that farming households would still need to depend on farming to meet a part of their requirements as the remittances will not be enough. In this case, farms would be left to manage on either old men or women. In several areas such as Bihar, Orissa, Kashmir, the farmer population is already showing signs of aging. Male farmer withdrawal is also leading to more number of women farmers in several parts of the country (Krishnaraj and Shah 2003). This raises important issues about the preparedness of the agricultural institutions and extension agencies to cater to the needs of women and old men as farmers. The 10th plan recognized the rights of women as farmers and there have been regular attempts to sensitize agricultural extension to the growing dominance of female farmers, however, on the ground the efforts are far from making a difference. There is a need for a fresh look at the changes in rural labor markets and changes in the roles played by men and women on the farms.

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Changing Consumption Patterns of India: Implications on Future Food Demand

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Introduction

Food grains dominate the vegetarian centered diet of the Indian people, although the composition varies across different regions. Grains provided 65 % of the calorie supply in 2000, and this varied from 60 % in the north to 74 % in the south. Rice is the main food grain in the south and the east, followed by wheat in the east and coarse cereals in the south; wheat is the principal food grain in the north followed by rice; and wheat comprises half of the grain consumption in the west, followed equally by rice and other coarse cereals. The non-grain food crops and animal products provided 27 % and 8 % of the remaining calorie supply in 2000. Due to cultural and religious reasons, the meat consumption in India is very low, and much of the animal product calorie supply at present is from milk and milk products. Milk consumption also varies significantly from 101 liters per person per year in the north to 26 liters in the south.

However, recent trends show shifts in food consumption patterns, with increasing consumption in non-grain food crops and animal products. The FAOSTAT data (FAO 2005) show per capita grain consumption has been decreasing since the 1980s. This decline is due to various factors, including income growth, urbanization and associated changes in life styles, changes in relative prices and the availability of non-grain food, etc. The National Sample Survey Organization (NSSO) survey results show that the average monthly per capita cereal consumption in the urban areas of India has decreased from 11.2 kg in 1973-1974 to 10.6 kg in 1993-1994. The corresponding decline in the rural areas is 15.3 kg and 13.4 kg, respectively. Within the grain products, there is a shift from coarse cereals to superior cereals such as rice and wheat (Viswanathan 2001). Nilkanth Rath 2003 has suggested that the per capita grain consumption will further decrease due to the reduction in physical labor requirement in rural areas. It is likely that these changing patterns will accelerate in the future with increasing income and urbanizations. The purpose of this paper is to capture these changing consumption patterns and assess their implication on India's food demand.

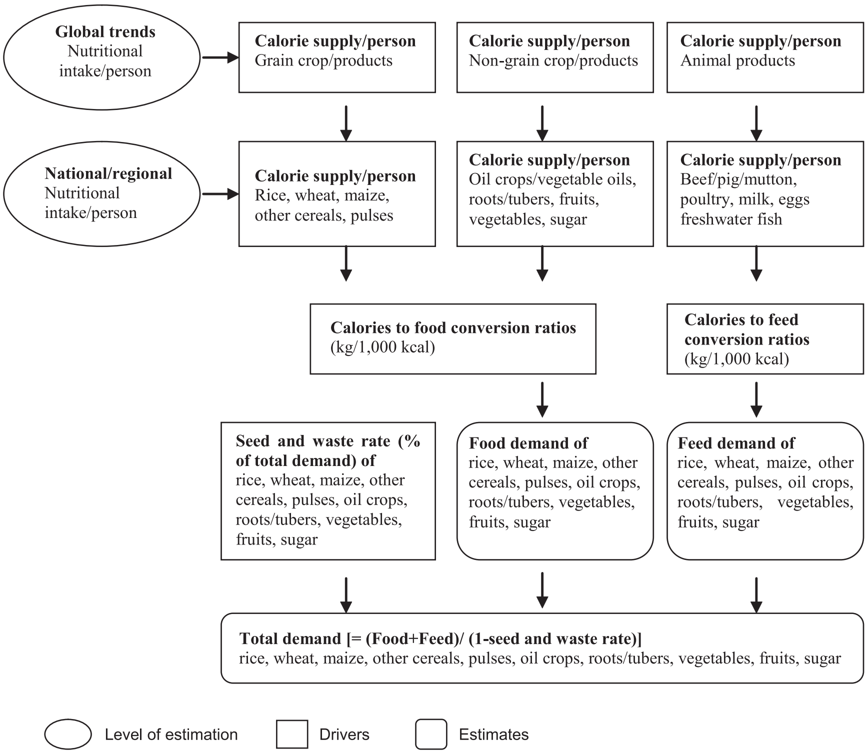
Several studies in the past have also projected India's food grain demand for 2020 (Bhalla et al. 1999; IWMI 2000; Kumar 1998; Rosegrant et al. 1995; Radhakrishna and Reddy 2004). These studies have, in varying degrees, accounted for the emerging trends of increasing animal product consumption and the resulting feed demand. However, most of the studies have concentrated only on the grain demand. Based on the spatial and temporal trends between 1987 and 1988 and between 1993 and 1994, Dyson and Hanchate 2000 have projected the grain and non-grain crop demand at the state level to 2020.

This study extends the projections of crop demand to 2050, by using the global, national and regional level changes of consumption patterns in recent times. The rest of the paper is divided into four sections. The next section explains the assumption and the methodology adopted in this paper. The third section presents the projections to 2025 and 2050, and compares them with the National Commission of Integrated Water Resources Development and other projection results (GOI 1999). The fourth section presents the implication of the increased grain demand projections on the water demand. We conclude the paper by discussing the policy implications and further research requirements.

Methodology, Data and Assumptions

The study assesses the demand for 12 major crops or crop categories (called only 'crops' hereafter). They include the grain crops: rice (milled equivalent), wheat, maize, other cereals (such as jowar, bajra, ragi, barley, millet etc.); and pulses and the non-grain crops: oil crops (including vegetable oils as oil crop equivalent), roots and tubers (dry equivalent), vegetables, fruits and sugar. FAOSTAT food balance sheets show that these crops accounted for 99 % of

Figure 1. Crop demand estimation for India.



the nutritional supply in the daily diets between 1991 and 2001, directly through food and indirectly through feed for the livestock (FAO 2005). Hence they were selected for the demand projection in this study. We also keep an allocation for seeds and waste.

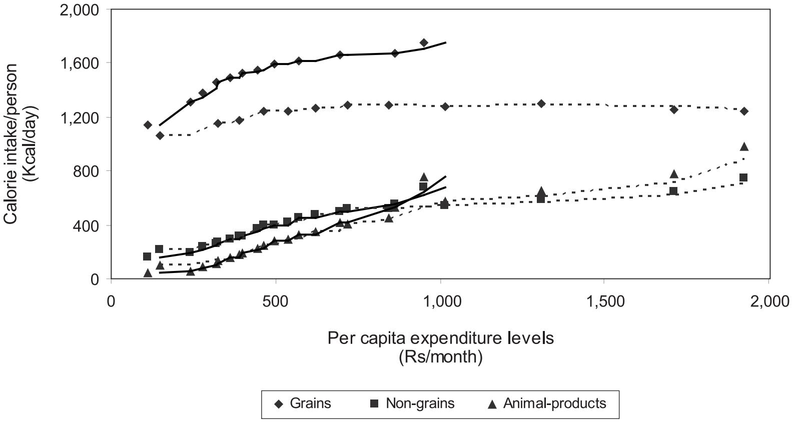
Figure 1 shows our approach to crop demand estimation. First we project the nutritional intake of grain, non-grain and animal product food categories using the global trends. Second, we assess the level of consumption of different crops or animal products that provide the projected calorie supply in the Indian context. Here we account for the regional variations of consumption patterns in India. Details of these are discussed next.

Nutritional Supply

Income and urbanization are two of the key drivers of changing nutritional intake patterns. In general, changing consumption patterns exist extensively in the middle - to high-income countries. Global consumption patterns show that, while food grains dominate the diets of the low-income categories, non-grain food products provide more than two-thirds of the daily calorie needs in the developing countries (FAOSTAT data, FAO 2005). As income and urbanization increases, the non-grain crops and animal product consumption increases. A significant diversification of diets occurs when people move away from the low-income to middle - and high-income categories. Differences of consumption pattern across different expenditure classes in India show high-income groups consume more non-grain crops and animal products.

We use the global consumption pattern to assess the trends of future calorie intake of the three food categories. Our approach is similar to the study by Knudsen and Scandizzo 1982, except that we use a sample of low- to middle-income countries to represent the variation of income. As India would only become an upper-middle-income country by 2050, we restricted our analysis to a sample of countries with GDP/person< US$10,000, and estimate the econometric relationship of the three calorie intakes against the GDP and urban population (Table 1). The calorie supply from grain products is very much regional or country-specific,

Figure 2. Calorie intake in rural and urban areas in India from 1999-2000.



Source: NSSO survey 55th round

Note: Solid and dash lines indicate the trends in rural and urban areas, respectively.

Table 1. Estimated regression equations.

Variables	Ln (CAL_i^G)		Ln (CAL_i^{NG})		Ln (CAL_i^{AP})	
	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
Constants						
Cluster 1 - α_{01}	6.85[a]	0.026	6.355[a]	0.116	4.30 [a]	0.208
Cluster 2 - α_{02}	0.204[a]	0.020	-0.115	0.085	-0.026	0.153
Cluster 3 - α_{03}	0.390[a]	0.021	-0.206[a]	-0.092	0.172	0.165
Cluster 4 - α_{04}	0.636[a]	0.022	-0.432[a]	-0.096	0.013	0.176
GDP						
α_1	-0.000002	-.000002	0.000478[a]	0.002	0.0012[a]	0.0001
GDP– middle income						
α_2	-	-	-0.000476[a]	0.0001	-0.0011[a]	0.0001
% Urban population						
α_3	-0.0035	.002	0.00430 [a]	0.002	0.0094[a]	0.0040
R^2	0.92		0.53		0.59	

Note: a- statistically significant at 0.05 level

and primarily depends on taste. This is evident in the statistically significant coefficients of the clusters with varying levels of grain consumption. Clusters 1 to 4 represents four homogeneous groups with grain consumption. Average daily intake of calories from grains in cluster 1 to 4 is 901, 1,130, 1,363, and 1,769, respectively.

At present, India's grain consumption is very high. On average daily calorie supply per person is 1,579 kcal. Therefore, income in India is not a significant driver any more of the grain consumption (Table 2). The negative but low elasticity of urbanization (Table 2) show that the changing rural-urban demographic patterns gradually contribute to the declining grain consumption. In fact, urbanization is contributing to about 97 % of the decline in the grain calorie supply in India.

With increasing income and urbanization, calorie supply of non-grain crops and animal products increases, but the rate of growth decreases in the middle-income countries. The elasticity estimates for India, show that while income growth contributes to a significant part

Table 2. Elasticity of calorie demand with respect to GDP and urban population growth.

Sources of growth	Elasticity in 2000 (GDP= US$463, PCTUP=28 %)			Elasticity in 2025 (GDP= US$1,765, PCUP=38 %)		
	Grains	Non-grains	Animal products	Grains	Non-grains	Animal products
GDP growth	-0.001	0.22	0.52	-0.004	0.11	0.32
Urbanization	-.097	0.12	0.26	-.133	0.16	0.36

(85 % in 2000) of the non-grain calorie supply change between 2000 and 2025, urbanization also contributes to the majority of this change after 2025. However, the income growth continued to be a significant factor of animal product calorie supply growth in both periods.

To assess the extent of the diversification of consumption patterns of different crops, we project the calorie intake of grains, non-grain crops and animal products in the Indian diet. For this projection we use global trends of energy intake of different food categories with respect to the changes in income and urbanization. We project India's calorie intake of grains, non-grain crops and animal products, with respect to the changes in income and urbanization from the levels of the base year 2000. The projections of calorie supply in 2025 and 2050 are given in Table 3.

Our projections show that non-grain crop products will dominate the Indian diet by 2050. The total calorie supply is projected to further increase, 15 % by 2025, and another 8 % by 2050. Almost the entire increase in calorie intake after 2025 is due to the increased consumption of non-grain crops and animal products. Our projections show a slight decline of the calorie supply from grains (9 %) by 2050, but significant increases in the non-grain crops (75 %) and animal products (144 %). The composition of calories supply from grain, non-grain and animal products changes from 63, 29 and 8 % in 2000 to 55, 33 and 12 %, respectively, by 2025 and 48, 36 and 16 %, respectively, by 2050.

Table 3. Calorie supply projections to 2025/2050 for India.

Year	GDP	Urban	Calorie supply/person/day			
	(person/year)	population (% of total)	Grains	Non-grains	Animal products	Total
	$	%	kcal	kcal	kcal	kcal
1990	313	25	1,640	562	163	2,365
2000	463	27	1,579	673	183	2,435
2025	1,765	37	1,520	912	343	2,775
2050	6,731	53	1,440	1,083	477	3,000

Source: Mamhood and Kundu 2006 (for urban population projection)

Note: GDP in 1995 in constant $ (source for 1990 and 2000 is WRI 2005). We assume a 5.5 % annual growth rate for 2025 and 2050 projections.

Composition of Nutritional Intake of Grains

The composition of the diet in different food categories depends on the taste and preference of the people, and as mentioned before, it varies significantly across regions. Thus, we need to take these differences into account in projecting individual crop demands. In India, there is a declining trend of consumption of coarse cereals. In 2000, rice and wheat contributed to most of the calorie intake (47 % and 31 %) from grains, while maize, other cereals and pulses contributed to 5, 9 and 7 %, respectively, of the calorie intake of grains. Dyson and Hanchate 2000, using the trends between 1987 and 1988 and 1993-1994 National Sample Survey Organization (NSSO) rounds observed that the per capita cereal consumption has declined in all states except in Kerala and West Bengal. The consumption of rice and wheat remains stable and decreasing coarse grain consumption was the major contributor to the cereal consumption decline.

Cereal consumption has further declined between 1993 and 1994 and 1999-2000 NSSO rounds, but the rate of decline had also decreased significantly. The cereal consumption/person/day before and after 1993-1994 NSSO rounds has declined by 1.19 and 0.74 % annually in the rural areas, and by 0.91 and 0.24 % in the urban areas. Within the cereal category, wheat consumption has shown no significant change (Table 4). However, a declining trend in rice consumption, especially in the rural areas, is seen in the post-1993-1994 NSSO rounds of surveys. The consumption of pulses remains unchanged at the 1987 level, though it had decreased before 1993-1994. In the urban areas, the consumption of other cereals has also declined further, but at a much slower rate than earlier. A notable trend, however, is the increasing rate of decline of rice consumption in the rural areas. Rural rice consumption per person has decreased 0.5 % annually after the 1993-1994 NSSO rounds against only a 0.05 % decline before the 1993-1994 NSSO rounds.

Table 4. Consumption/ person of grain crops in India.

Year	Rice		Wheat		Maize		Other cereals		Pulses	
	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban
Past trends (annual growth rates, %)										
1987-1993	-0.05	-0.42	-0.60	0.27	-4.97	-6.78	-4.97	-4.97	-2.40	-1.62
1993-1999	-0.50	-0.10	0.50	0.04	-5.03	-2.77	-5.03	-2.77	4.37	4.45
Projected annual growth (%)										
2000-2025	-0.04	-0.01	0.00	0.00	-0.40	-0.22	-0.40	-0.22	0.00	0.00
2000-2050	-0.11	-0.02	0.00	0.00	-1.06	-0.59	-1.06	-0.59	0.00	0.00
Consumption/person/month in India (kg)										
2000	6.78	5.15	4.80	4.89	1.10	0.09	1.72	0.67	0.93	1.04
2025	6.71	5.14	4.80	4.89	0.99	0.09	1.55	0.63	0.93	1.04
2050	6.43	5.10	4.80	4.89	0.64	0.07	1.01	0.50	0.93	1.04

Sources: The trends are estimated from the data of NSSO rounds in 1987-1988, 1993-1994, and 1999-2000 (NSSO 1996, 2001). The 2025 and 2050 projections are authors' estimates.

We project that the composition of grains in the diet will further change, but will soon reach a steady state in both rural and urban areas. As in Dyson and Hanchate,[1] we use recent trends to project future demand, but subject to the restriction that the total calorie supply/

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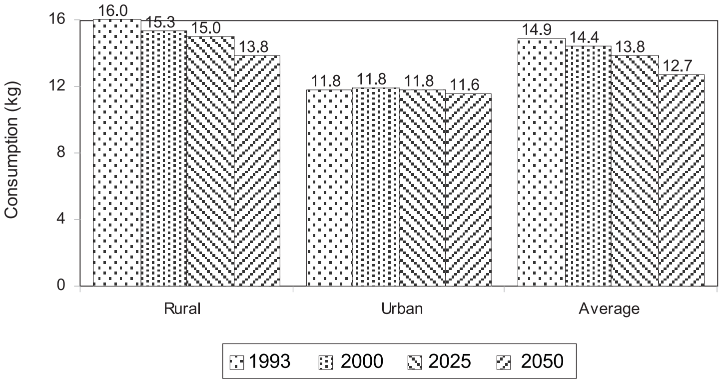
[1] Dyson and Hanchate 2000 project the cereal consumption/person/month in the rural and urban sectors to decrease from 15.1 and 12.3 kg in 1993-1994 to 12.7 and 10. 9 kg by 2020. Other studies based on expenditure elasticity have projected an increase in per capita cereal consumption by 2020 (Bhalla et al. 1999). However, many argue (Dyson and Hanchate 2000; Bansil 1995) that due to the complex nature of taste and preferences, and changes in life styles across states and across income classes, the estimated elasticity may also change in the future.

person/day of grain products will be 1,520 kcal in 2025 and 1,440 kcal in 2050 (Table 4). As the long-term trends show no significant change, we assume that the per capita consumption of wheat and pulses remains the same in the rural and urban areas. The adjusted growth rates of per capita consumption are given in Table 5. The rural rice consumption per person is projected to decrease from 6.78 kg per month in 2000 to 6.43 kg per month by 2050.

The final projections of grain consumption at the national level depend not only on the level of per capita consumption in rural and urban areas but also on the population change. A recent study projects that India's total population will increase from 1,027 million in 2001 to 1,383 million in 2025, and to 1,585 million by 2050 (Mahmood and Kundu 2006). And the rural population, as a share of total population will decrease from 72 % in 2000, to 63 and 47 % by 2025 and 2050, respectively. As a result, the rural-urban differential of the consumption and increasing urban population, average grain consumption/person/month declines at a faster rate than in rural and urban areas (Figure 2). The composition of calorie supply of rice, wheat, maize, and other cereals and pulses will change from 47, 31, 5, 9 and 7 % in 2000 to 48, 33, 4, 8, 7 %, respectively in 2025 and 49, 35 , 3, 5 and 8 %, respectively, by 2050.

Figure 2. Grain consumption/person/month.



Sources: 1993, 2000 data from NSSO rounds. 2025 and 2050 are authors estimates.

Composition of Calorie Supply of Non-grains

The consumption of non-grain crops such as fruits, vegetables and edible oils, will prominently feature in the future Indian diet. Kanchan Chopra 2003 and Dyson and Hanchate 2000 have noted that fruit and vegetable consumption will increase significantly by 2020. Our projections of the nutritional intake indeed, show that the contribution of the non-grain crops to the total calorie supply is expected to increase from 29 % in 2000 to 33 and 37 % by 2025 and 2050, respectively. How is the composition of non-grain crops changing?

The oil crops (including edible oil) and sugar products provided 79 % of the calorie supply of non-grain crop products (Table 5). While the contribution of oil crops to the total calorie supply has increased over the years (34 % in 1980 to 42 % in 2000), the contribution from sugar products has decreased from 43 % to 37 % over the same time period. The contribution of roots and tubers, vegetables and fruits shows no major changes (9 %, 7 % and 7 % in 1980 to 7 %, 7 % and 8 % in 2000). Where the per person consumption is concerned, fruits, vegetables and oil crops have shown a substantial annual growth in the last decade.

Indeed, the calorie supply from oil crops and sugar in India (528 kcal/person), compared with other developing countries (273 kcal/person), is significantly higher now. But this is much lower than the calorie supply in the developed countries (871 kcal/person). Fruit and vegetable consumption, which is highly income-elastic, provides 96 kcal/person, and this is much lower compared with that in other developing countries (170 kcal/person). However, with increasing income and urbanization, fruit and vegetable consumption is projected to increase rapidly. We use this information to project the composition of calorie supply of non-grain crops in the future.

Table 5. Calorie supply from non-grain crops.

Year	Total	Oil crops	Roots and tubers	Vegetables	Fruits	Sugar
Calorie supply from non-grain crops (kcal/person/day)						
1980	449	152 (34)	41 (9)	32 (7)	31 (7)	193 (43)
1990	526	195 (37)	40 (8)	35 (7)	34 (7)	221 (42)
2000	673	281 (42)	49 (7)	45 (7)	51 (8)	247 (37)
2025	912	442 (49)	66 (7)	67 (7)	63 (7)	274 (30)
2050	1,083	500 (46)	105(10)	75 (7)	87 (8)	316 (29)
Annual growth (%)						
1980-1990	1.7	2.5	-0.3	0.9	1.0	1.4
1990-2000	2.5	3.7	2.0	2.4	4.1	1.1
2000-2025	1.2	2.2	0.9	1.6	1.9	0.6
2000-2050	0.9	1.3	1.4	1.0	1.6	0.6

Sources: 1980-2000 data are from FAO 2005. The 2025, 2050 data are the authors' projections.

Note: Numbers within parentheses show the percentage of the total calorie supply.

As in the estimation of grain crop consumption, the annual growth rates of the consumption per person between the 1993-1994 and 1999-2000 NSSO rounds are used for projections of non-grain crops (Table 6). First, we project per person rural and urban consumption demand. The state-level consumptions are projected according to the differences of state-level growth rates. However, two adjustments on the growth rates are necessary before we make future projections. First, with annual growth rates from1993-1994 and 1999-2000, NSSO rounds, the total calorie supply projection from the non-grain products is much higher than the projected total in Table 5. Therefore, we adjust the annual growth rates of rural and urban sectors so that the total calorie supply per person of non-grain products will be 940 kcal in 2025 and 1,140 kcal in 2050. Second, even with this adjustment, the calorie supplies of oil crops and vegetables in 2050 are unrealistically high, and they are even higher than the levels of the highest-consuming countries at present. Therefore, we set a ceiling for the per capita consumption of these crops, 500 kcal for oil crops, and 75 kcal for vegetables by 2050, a level comparable to the highest consumption in the developing world.

The projections of the per capita consumption of vegetables and fruits in our study for 2050 are even lower than those of the Dyson and Hanchate 2000 for 2020. They project that the rural and urban vegetable consumption per person increases to 162 and 140 kg/year by 2020, respectively, and that the fruit consumption increases to 39 and 78 kg/year by 2020, respectively. The calorie supply from this level of vegetable and fruit consumption (170 kcal/person) is even higher than the present-day calorie supply of the developed countries. The growth assumptions in our study, however, are less rigid, and we believe they will result in more realistic projections by 2025 and 2050.

Table 6. Consumption of non-grain crops in India.

Year	Oil cops		Roots and tubers		Vegetables		Fruits		Sugar	
	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban
Past trends (annual growth rates (%))										
1987-1988	3.9	3.3	1.4	0.3	3.9	0.2	1.6	1.9	-1.3	-0.2
1993-1999	6.6	5.9	5.1	3.7	6.1	5.8	2.0	1.8	1.7	0.7
Projected annual growth (%)										
2000-25	1.7	1.5	1.3	1.0	1.6	1.5	0.5	0.5	0.4	0.2
2000-50	1.0	0.9	1.8	1.3	1.0	0.9	0.7	0.7	0.6	0.2
Consumption/person/year in India (kg)										
2000	37	53	6	5	68	72	31	64	25	29
2025	57	77	8	6	100	105	35	72	27	30
2050	62	83	15	10	111	116	44	89	33	32

Food Demand

The total food demand projections for 2025 and 2050 are given in Table 7. We use the state-level population projections of Mahmood and Kundu 2006 for estimating the total food demand. According to this demographic projection, the rural population will increase from 729 million in 2000 to 879 million in 2025 and then decrease to 776 million by 2050. The urban population will increase from 278 million in 2000 to 510 million in 2025 and to 810 million by 2050. Overall,

Table 7. Total food demand projections in 2025 and 2050.

Food demand (Mmt)

Year	Grain	Rice	Wheat	Maize	Other cereals	Pulses	Oilcrops	Roots and tubers	Vegetables	Fruits	Sugar
1990											
2000	173	76	58	10	17	12	42	6	70	40	26
2025	230	102	81	11	20	16	89	11	142	67	39
2050	241	109	92	7	14	19	115	19	180	106	52

Source: 1990 and 2000 data from FAOSTST (FAO 2005). Figures for 2025 and 2050 are authors' estimates.

the total population will reach the peak of about 1,580 million by 2050 and will start to decline thereafter. More than half (53 %) the total population will be in urban areas by 2050.

Feed Demand

At present, India's feed grain demand is very low due to the low level of animal product consumption. In 2000, animal products contributed to only 7 % of the daily calorie supply. And milk and milk products provided the bulk (91 %) of this calorie supply. Much of the feed demand for producing this calorie supply at present is met through open grazing, crop residues, food waste, oil cakes, etc. The total feed grain use in 2000 was only 8 Mmt, which is only 4 % of the total grain use. However, feed demand is expected to increase much faster with increasing animal products in the diet.

Our nutritional intake projections show that the animal product calorie supply will increase 89 % between 2000 and 2025; and further 54 % between 2025 and 2050. Recent trends show that the consumption of poultry products, eggs and freshwater fish is rapidly increasing (Table 8). Due, mainly, to religious and cultural reasons, meat consumption, especially beef and pork, is very low and has posted no significant growth in the last few decades. Milk consumption, 98 kg/person/year, which is relatively high compared to that in developing countries, increased at 0.8 annually in the 1990s.

If recent trends are indications of the future, then milk products will still dominate the animal product consumption. The share of poultry products will also increase substantially. We use the trends between 1993 and 1994 and 1999-2000 NSSO rounds for projecting the future demand of animal products. And we subject the projections to the constraint that the total calorie supply from the animal products does not exceed the projections of 341 and 478 kcal/

Table 8. Consumption of animal products in India.

Year	Beef/pork/mutton		Milk products		Poultry products		Eggs		Freshwater fish	
	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban
Past trends (annual growth rates (%))										
1987-1988	1.8	-2.7	3.4	2.3	0.0	7.0	3.5	0.6	2.0	2.7
1993-1999	1.6	1.0	-0.5	0.8	12.2	12.2	9.3	5.7	2.6	1.6
Projected annual growth (%)										
2000-2025	1.5	0.9	0.7[1]	0.7	11.4	11.4	8.7	5.3	2.4	1.5
2000-2050	1.1	0.6	0.5[1]	0.5	8.2	8.2	6.3	3.8	1.8	1.1
Consumption/person/month (kg)										
2000	0.28	0.47	4.81	7.33	0.07	0.13	0.09	0.18	0.23	0.24
2025	0.46	0.63	6.14	9.36	0.42	0.85	1.56	1.07	0.53	0.40
2050	0.53	0.69	6.59	10.04	0.74	1.48	3.74	1.82	0.68	0.47

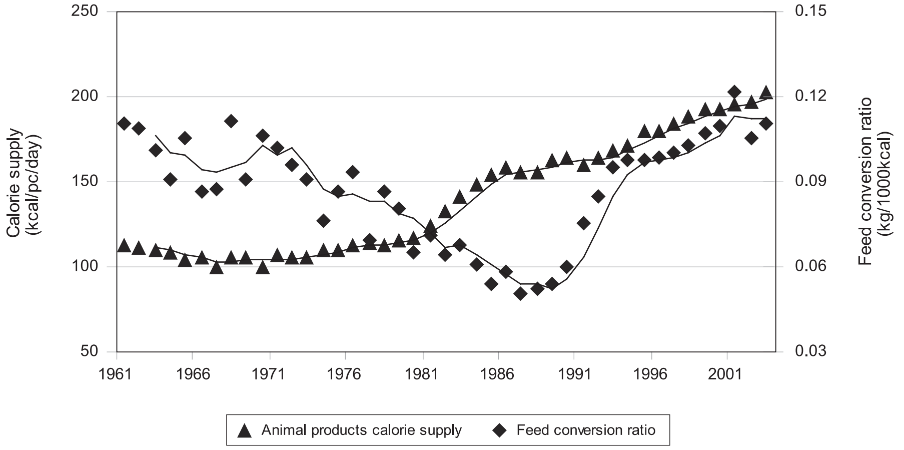
Source: Past trends estimated from the data of NSSO rounds in 1887-1888, 1993-1994, and 1999-2000 reports (NSSO 1996, 2006). The consumption data of NSSO 1999-2000 are adjusted to match FAOSTAT totals of 2000. The projections are authors' estimates.

Note: [1] The growth of milk consumption in the rural areas during 1993-1990 was negative. We assume that it would increase at the same rate as in the urban areas in the future.

person/day in 2025 and 2050, respectively. The projections show that milk products will still contribute to 66 % of the calorie supply by 2050. But the share of calorie supply from poultry products will increase from only 1 % in 2000 to 20 % by 2050. Since poultry farming mainly operates at a commercial level, the consumption increase will have a substantial impact on the feed grain demand.

This paper uses feed conversion ratio (FCR) to estimate the feed grain demand. FAOSTAT data show that the feed conversion ratio of grain was decreasing until the late 1980s (Figure 3). During this period, the growth of feed use has not matched the pace of increasing animal product calorie supply. However, with increasing use of grains, especially maize, for livestock, the FCR started moving upwards since the late 1980s. Between 1988 and 1995, the FCR increased at 9.3 % annually. Over this period, the calorie supply from animal products increased at 1.6 %, while the feed grain use increased at 13.2 %. The growth of FCR between 1995 and 2002 was 1.9 %. During this period, the calorie supply of animal products increased annually at 1.6 % while feed grain use increased at 5.3 % annually.

Figure 3. Growth of animal product calorie supply per person and feed conversion ratio of grains.



We use the growth rates of feed conversion ratios between 1995 and 2002 to project feed use for 2025 and 2050. First, we project the feed conversion ratios of grains. The growth rate of feed grain conversion ratio is adjusted according to the growth rates of the animal product calorie supply. The animal product calorie supply is projected to increase by 2.2 and 1.7 % in the periods 2000-2025 and 2000-2050, respectively, while the feed conversion ratios are projected to increase by 2.7 and 2.0 % in the corresponding periods. The projected FCR of grains by 2025 is 0.37 kg/1,000 kcal, and is slightly higher than the FCR of China in 2000 (0.34 kg/1,000 kcal), but still much lower than the developed countries (0.74 kg/1,000 kcal).

With the projected feed grain conversion ratios, the feed grain demand will increase 4.6 times by 2025; and 13.7 times by 2050, from the level of 8 Mmt in 2000 (Table 9) . Next we estimate the individual grain crop demand. Here we adjusted the growth rates of feed conversion ratios of individual crops by a similar factor subject to the constraint that the total feed demand of individual crops is equal to the projected feed grain demand.

Table 9. Feed consumption.

Factors	Grains	Rice	Wheat	Maize	Other cereals	Pulses	Oil crops	Roots and tubers	Vegetables	Fruits	Sugar
Feed conversion ratios in kg/1,000 kcal											
1995	0.098	0.005	0.012	0.054	0.007	0.020	0.013	0.000	0.000	0.000	0.007
2000	0.113	0.004	0.011	0.077	0.005	0.015	0.010	0.000	0.000	0.000	0.005
Annual growth rates of feed conversion ratios (%)											
1995-2002	2.0	-2.6	-1.7	5.4	-4.2	-4.2	-3.2	0.0	0.0	0.0	-2.7
2000-2025	2.7	-1.9	-1.3	4.0	-3.1	-3.2	-2.4	0.0	0.0	0.0	-2.7
2000-2050	2.1	-1.4	-1.0	3.0	-2.3	-2.3	-1.8	0.0	0.0	0.0	-2.7
Feed demand (Mmt)											
2000	8.1	0.4	0.9	5.3	0.4	1.2	0.6	0	0	0	0.4
2025	37.5	0.5	1.5	33.8	0.4	1.2	0.8	0	0	0	0.3
2050	111.2	0.6	1.8	107.4	0.3	1.0	0.8	0	0	0	0.1

Source: Authors' estimates are based on FAOSTAT data.

The majority of the feed demand increase is for maize. According to estimates of the United States Department of Agriculture (USDA), 42 % of the maize production at present is for feed in the poultry sector. And with increasing consumption of poultry products, maize demand for feed will increase rapidly (Landes et al. 2004). Our projection shows that the consumption of poultry meat and eggs is projected to increase at 9 % and 5 % annually over the next 50 years. Poultry production of this magnitude can only be sustained under commercial farming and much of the feed demand in this sector will be met from maize. And we project that the maize demand for feed will increase 6 % annually over the next 50 years.

Total Crop Demand

The rates of seed, waste and other uses (i.e., as a percent of total domestic use) of many crops have slightly decreased over the last decade (Table 10). However, the waste of maize, roots and tubers and fruits is still substantial. With improved post-harvest technologies and storage facilities, and with increased transport facilities and marketing in the rural areas, waste rates of all crops are expected to decline. We use the trends between 1990 and 2000 to project future seed and waste rates subject to the following constraints. If the projected values of the combined seed and waste rates fall below the seed rates in 2000, then we assume the seed rates in 2000 for the projection. Second, if the growth rates of seeds and waste rates show an increasing trend in the 1980s and 1990s, then we assume the seed and waste rates in 2000 for the projection.

The projected seed and waste rates of all crops, except oil crops, roots and tubers, and fruits, are lower according to our projections. The share of the waste in the rates of seed, waste and other uses of roots and tubers, and fruits is high and has been increasing in the past. But, better storage and transport and marketing facilities would have a significant impact in reducing waste in these two crops. However, the information available now is not sufficient to assess the extent of the waste reduction of these crops. So we assume the rates in 2000 for future projections. With the projected rates of seeds, waste and other uses, we are now set to estimate the total crop demand (last three rows of Table 11).

The total grain demand is projected to increase by 45 % and 88 % in 2025 and 2050, respectively. The increasing maize demand, especially for feed, contributes to much of the total grain demand increase. The total grain demand is projected to increase by 176 Mmt between 2000 and 2050. The maize demand increase, of 101 Mmt, contributes to 57 % of the additional grain demand. Although the rice and wheat demand increases are the same (35 Mmt), the level of increase of wheat demand over the 2000 consumption level is significantly higher. Another important observation is the increasing demand of non-grain crop products. The demand for non-grain crops will more than double over the next 50 years.

Table 10. Seed and waste rates and total crop demand.

Factors	Grains	Rice	Wheat	Maize	Other cereals	Pulses	Oil crops	Roots and tubers	Vegetables	Fruits	Sugar
Seeds and waste rates of total consumption (%)											
1980	10.2	8.3	12.8	19.6	9.4	10.2	18.9	16.4	7.2	12.9	0.02
1990	10.1	7.6	12.1	19.3	9.4	9.0	11.3	18.9	7.0	13.2	0.03
2000	9.6	6.8	11.7	17.0	9.7	8.2	12.7	19.2	6.7	14.0	0.04
Projected seeds and waste rates as a percent of total consumption											
2025		5.9[b]	9.9	10.1	9.7[a]	5.9[b]	12.7[a]	19.2[a]	5.5	14.0[a]	0.04[a]
2050		5.9[b]	8.3	6.0	9.7[a]	5.9[b]	12.7[a]	19.2[a]	4.5	14.0[a]	0.04[a]
Total crop demand (Mmt)											
2000	201	82	67	18	20	14	49	7	75	47	26
2025	291	109	91	50	23	18	103	13	150	78	40
2050	377	117	102	121	16	21	133	24	189	123	52

Notes: [a] An increasing trend is seen in the growth of seeds and waste rates from 1980 to 2000. For them, we project the seeds and waste rates at the 2000 level.

[b] The decreasing trends are significant in that the projected seeds and waste rates fall even below the seed rate in 2000. For them we assume the seed rates at the 2000 level.

Comparison with Other Food Demand Projections

We started our projections analyses with a view to assessing the impacts of recent consumption pattern changes on the NCIWRD commission's grain demand projections. A part of the deviation of various demand projections is attributable to the different assumptions of the total population projections. In order to make proper comparison, we standardized the projection to the same level of population as illustrated in Dyson and Hanchate 2000. Table 11 summarizes six demand projections. The latter four studies only estimate cereal demand. Therefore, the per capita demand of these studies is adjusted by adding the pulses demand of the present study (12 kg for food and 13 kg for total). The totals are adjusted to the population of 1,315 million by 2025 as projected by Dyson and Hanchate 2000, and of 1,581 million by 2050 as assumed by the NCIWRD commission.

Table 11. Grain demand projections of different studies.

Source of study	Demand/person (kg/year)				Total demand (Mmt)			
	2025		2050		2025		2050	
	Food	All	Food	All	Food	All	Food	All
Present study	166	210	152	238	218	276	241	377
NCIWRD	215	240	279	312	283	316	441	494
Dyson and Hanchate	159	182	-	-	209	239	-	-
Kumar	179	190	-	-	235	250	-	-
Bansil	180	202	-	-	237	266	-	-
Bhalla et al.	197	235	-	-	259	309	-	-

Sources: GOI 1999; Dyson and Hanchate 2000; Kumar 1998; Bansil 1999; Bhalla et al. 1999.

The present study and the NCIWRD projections differ in both food and feed consumption demand. The commission assumed a substantially high food grain consumption per person assuming a well-fed scenario for India. And for the well-fed scenario, the commission assumed a substantially high proportion of the nutritional intake from the food grains. But as discussed in the introductory section, this assumption converts to a substantially higher calorie intake per person, which is not realistic with the present trends of grain consumption in India or even in other developing countries in the world. Our study results differ a great deal from the commission's projections with respect to other non-grain crop and animal product consumptions. The non-grain food consumption will provide the majority of calorie intake in the present study (53 % in 2050, as against 35 % in 2000). The increased consumption of animal products, especially milk and poultry products in the present study, is reflected in a substantially high difference in the total and food grain demand. The feed grain demand comprises much of this difference.

The food demand projection of this study (166 kg/year in 2025) is higher than that of Dyson and Hanchate 2000, but lower than the latter three projections. Contrary to the current trends, Kumar, Bansil and Bhalla et al. studies projected increasing per capita cereal consumption. Dyson and Hanchate's projection is compatible with the current trends. But it is based by extrapolating the trends between 1987 and 1988 and 1993-1994 NSSO rounds. But the present study reflects the recent trends observed after the 1993-1994 NSSO survey.

The total grain demand projection of this paper is more closer to the Bansil 1999 and Bhalla et al. 1999 projection, primarily due to high feed demand for livestock. Is the nutritional supply of the projected consumption in the present study adequate for feeding well all the people in India by 2050? This study projects the average calorie supply at 3,000 kcal/ person/ day by 2050, and according to David Seckler (IWMI 2000), the average daily calorie intake of 2,700 kcal at the national level is adequate for providing the minimum nutritional intake of even the lowest income strata of any country (the minimum nutritional requirement of India is estimated to be about 2200 kcal/person/day). Indeed, the average calorie intake of the developed countries is 3200 kcal/person/day, and nutritional poverty is almost non-existent in these countries. However, barring any distributional difficulties, which will be much lower with better infrastructure in 50 years time, the projected food consumption will be adequate to provide the minimum nutritional supply for much of the Indian population.

Conclusion

This paper started assessing the recent food consumption pattern shifts in India and their implication for total crop demand. The recent trends clearly show changing patterns of consumption. While direct grain consumption is decreasing, non-grain product consumption in the daily diet is increasing in both rural and urban areas. This study projects that, with increasing income and urbanization, the non-grain crops and the animal products (dairy and poultry) would dominate the consumption basket by 2050. The contribution of grain products to the total calorie supply is projected to decrease from 65 % in 2000 to 55 and 48 % by 2025 and 2050, respectively. However, the total calorie supply is projected to increase to about 2,770 and 3,000 kcal/person/day by 2025 and 2050, respectively. This level of average calorie supply is sufficient for providing adequate nutritional security to the people even in the lowest income percentiles.

A major implication of the changing consumption pattern is the increasing feed grain demand. The total grain demand will increase from 201 Mmt in 2000 to 291 and 377 Mmt by 2025 and 2050, respectively. The feed demand is projected to increase many times, from a mere 8 Mmt at present to 38 and 117 Mmt by 2025 and 2050, respectively. The increasing feed grain demand is projected to consist of a major part of the total grain demand increase, 33 and 83 % respectively over the periods 2000-2025, and 2025-2050. The food demand projection in this study is significantly different from the NCIWRD projections. According to the commission, food grains provide the bulk of the nutritional demand in the future. This study holds a diametrically opposite view. The total food grain demand in the present study in 2050 is only 241 Mmt but the commission projects 441 Mmt. The total grain demand of the present study is 117 Mmt less than the commission projections. Thus, as mentioned in the introduction, the reservations expressed by many on the NCIWRD's projection increase in irrigated area (by 30 Mha), which is based on increased food grain demand, are justifiable. Thus, food grain demand cannot be a justification for large-scale water transfers such as aimed at by India's river linking project.

Another implication of the changing consumption patterns is the high level of consumption of non-grain crops. The demand for oil crops (including edible oil), vegetables and fruits will increase several times from the present level. In fact, India's predominance of food grains in the agriculture consumption and production patterns is changing. A major challenge for Indian agriculture in the next few decades in this century is how to meet the increasing demand for the feed grains. And even a greater challenge in the future is how India is going to meet the increasing demand for non-grain crops. The study shows the need for the diversification of future agricultural production, especially to high-value non-grain crops. The increasing demand for non-grain crop products will outpace the increasing demand for grains. Where and to what extent the crop diversification is possible depends on the access and availability of water resources and how they are consumed.

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Indian Agriculture: Recent Performance and Prospects in the Wake of Globalization

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Introduction

Following macroeconomic reforms introduced in the Indian economy in the early 1990s, and the reforms in the multilateral trading order brought about in the wake of GATT negotiations and the setting up of the WTO, the Indian agriculture has entered into the phase of globalization and diversification. It is expected that the combined effect of the reforms in the domestic policies and international trade reforms would result in a much larger integration of the Indian economy with the rest of the world, and such a scenario would bring about substantial benefits to the Indian farmers. The reforms undertaken so far have, however, failed to bring about the expected gains to Indian farmers. The process of reforms is still continuing and it is hoped that once the negotiations on reforms conclude and the envisaged reforms are implemented in letter and spirit, the gains to Indian agriculture would be positive and substantial.

To realize the expected gains from trade liberalization, apart from improvement in infrastructure, the Indian agriculture would need to become more competitive. The recent deceleration of growth in Indian agriculture - both in production as well as in crop productivity - has however been a cause of worry. Unless this trend is reversed, India may not be able to take on the opportunities that may be made available to it in the wake of globalization.

Based on some of the available literature on the subject, the present paper attempts to present a brief review of the recent growth performance of Indian agriculture and some of the agricultural support policies that have a major impact on agriculture. The paper provides a brief description of the status of WTO negotiations in agriculture and the Indian stand on some of these issues under negotiation. In the light of this discussion the paper then gives a brief review of some of the recently conducted studies on the potential impacts of these negotiations on agricultural prices, trade, production and welfare.

Performance of Indian Agriculture

India is the second largest producer of food in the world, its share being more than 200 million tonnes of food grains, 150 million tonnes of fruits and vegetables, 91 million tonnes of milk, 1.6 million tonnes of poultry meat, 417 million livestock, and 6.05 million tonnes of fish and fish products. The Indian agriculture has made great strides over the years. The US$ food grain production has increased more than four fold - from 51 million tonnes in 1950-51 to 212 million tonnes during 2003-04 growing at an annual average rate of more than 2.4 % per annum (Tables 1 and 2). The recent trends in the performance of Indian agricultural production, however, present a dismal picture. During the 1990s, there has been a deceleration in the production of all the principal crops. The growth in production of 'all principal crops' decelerated from 3.19 % per annum during the decade of 1980s to 2.29 % per annum during the decade of 1990s. During the first 4 years of the current decade the growth rate so far has been a mere 0.70 %. It is not only the growth at the aggregated level that has decelerated, similar pattern has been observed in the case of growth rates of almost all the crops. While the growth in production of food grains has fallen from 2.85 % in 1980s to 2.02 % in 1990s and a mere 0.27 % in the current decade so far, the growth of non food grains during the corresponding periods has declined from 3.77 % to 2.69 % to 1.35 %. The growth in the yields of principal crops notably rice and wheat has also decelerated. The overall growth

Table 1. Annual production of important crops during selected periods (million tonnes).

TE ending	Food grains	Rice	Wheat	Coarse cereals	Total pulses	Oilseeds	Cotton	Sugarcane
1980-81	123.73	49.91	34.55	31.24	10.46	7.95	7.95	144.91
1990-91	172.45	72.78	53.03	53.03	13.66	8.42	8.42	223.22
2000-01	203.41	86.91	72.45	72.45	13.14	6.88	6.88	294.67
2003-04	199.70	84.33	69.98	69.98	13.25	6.57	6.57	271.65

Table 2. Compound growth rates of production and yield of important crops.
(Base TE 1981-82=100) (% Per annum.)

	Production			Yield		
Crop	1980-81 to 1989-90	1990-91 to 1999-00	2000-01 to 2003-04	1980-81 to 1989-90	1990-91 to 1999-00	2000-01 to 2003-04
Rice	3.62	2.02	-1.47	3.19	1.34	0.88
Wheat	3.57	3.57	-0.12	3.10	1.83	-0.53
Coarse cereals	0.40	-0.02	3.48	1.62	1.82	3.54
Total cereals	3.03	-0.02	-0.53	2.90	1.59	0.85
Total pulses	1.52	0.59	8.01	1.61	0.93	3.22
Food grains	2.85	2.02	0.27	2.74	1.52	0.94
Sugarcane	2.70	2.73	-6.79	1.24	1.05	-5.01
Oilseeds	5.20	1.63	5.17	2.43	1.15	5.02
Cotton	2.80	2.29	10.22	4.10	-0.41	15.9
Non food grains	3.77	2.69	1.35	2.31	1.09	2.40
All principal crops	3.19	2.29	0.70	2.56	1.33	1.53

Source: Government of India 2004

rate of the yield of all the principal crops has decelerated from 2.56 % in 1980s to 1.33 % in 1990s and has recovered slightly to 1.53 % during the 4 years of the current decade. While the growth in food grain production during the 1990s has managed to be just equal to population growth rate (2.02 % versus 2.16 %), the preliminary data for the more recent years indicate a food grain production growth rate far behind the population growth rate. In fact, the underlying trend of rice and wheat production was already less than population growth by the end of the Ninth Plan. The official data show that the net per capita availability of food grains in the country came down from 471 gram per capita per day during the TE ending 1990 to 456 gram per capita per day during the TE ending 2000.

Apart from occasional poor monsoons and some demand-related problems, the long-term trend of agricultural production in India can largely be attributed to a variety of factors such as declining public investment; failure to carry out essential reforms to conserve water and soil; unabated degradation of natural resources, and weakened support systems due to financial problems of state governments. While reversing the trend of declining investment in agriculture, often cited as the most important factor for deceleration in growth, especially during the 1990s, could contribute significantly to reversing the observed deceleration in the growth of agriculture, it will not, however, be prudent to expect that investment alone will reverse this trend. In order to make investment in agricultural infrastructure yield the desired results in terms of higher productivity and production, it would be imperative to pursue reforms vigorously in many areas such as agricultural research, extension, credit, marketing, etc., since these reforms collectively would determine the reduction in cost of production and profitability of agriculture. It is the profitability that would ultimately drive the engine of innovation, entrepreneurship and growth.

India’s Agricultural Trade: Some Recent Trends

Exports

India has been both an importer and exporter of agricultural commodities for a very long time. India’s agricultural exports after growing at a rate of only 0.78 % per annum during the period from 1961 to 1971, registered a steep hike and during the period 1971 to 1981 increased at an annual average growth rate of 18.36 %. During the decade of 1980s the growth rate of exports again plummeted to 2.24 % per annum. The economic liberalization and trade reforms introduced in 1991, helped India accelerate the growth rate of exports to 7.42 % per annum (Bhalla 2004). While during the first half of the 1990s India’s agricultural exports performed extremely well, however since 1995-96 these have shown extreme fluctuations. Although the World Trade Organization (WTO) Agreement on Agriculture in 1995 was expected to improve India’s agricultural exports, this does not seem to have happened. There have recently been some signs of a turnaround during 2002-03 and it is expected that this trend will continue. Bhalla 2004, however, opines that this sudden surge in Indian exports has to some extent been the result of the existence of large stocks and transport subsidy made available to exporters.

Examined from another angle, the share of agricultural exports, which constituted more than 30 % of the total exports from the country during 1970-71 and 1980-81, have of late been declining consistently, more so in recent years. The declining trend is more noticeable in the post liberalization and post WTO periods. In 1990-91 agricultural exports constituted about 18 % of the total exports which in 2000-01 went down to 14 %. In 2003-04 agricultural exports constituted only 12.4 % of all exports (Table 3). Although the relative share of agriculture in total exports has been falling over time and is also lower than that of some other developing countries, the share of agricultural products in total export earnings is still substantial. While the declining share of agricultural exports in total exports is explained primarily in terms of the relatively faster growth in the volume of merchandise exports, it appears that there are other and more fundamental reasons which underlie the sluggishness of agri-exports from India. Further, not only the share of agricultural exports in the total merchandise exports came down steadily over the years but the share of agricultural exports (including processed food) in agricultural GDP also declined from 7.6 % in 1995-96 to 6.3 % in 2001-02 and recovered marginally to 6.9 % in 2003-04.

Table 3. Exports of agricultural commodities from India (value in million US$).

Year	Total exports	Agricultural exports	Agr exports as % Total exports
1960-61	1,348	596	44.21
1970-71	2,031	644	31.71
1980-81	8,484	2,600	30.64
1990-91	18,145	3,354	18.49
1991-92	17,865	3,203	17.93
1992-93	1,537	3,136	16.92
1993-94	22,238	4,028	18.11
1994-95	26,331	4,226	16.05
1995-96	31,795	6,082	19.13
1996-97	33,470	6,863	20.50
1997-98	35,006	6,626	18.93
1998-99	33,219	6,035	18.17
1999-00	36,822	5,773	15.68
2000-01	44,560	6,256	14.04
2001-02	43,827	6,146	14.03
2002-03	52,719	6,962	13.21
2003-04	63,843	7,888	12.36

The experience of India since 1971 confirms that growth of agricultural exports from India is highly correlated with the growth rate of international trade in agricultural commodities. The recent slow down in Indian exports since mid-1990s can also be attributed to a slow down in international trade in the latter half of the 1990s. A complementary factor for rapid growth of agricultural products during the early 1990s was the high prices of agricultural commodities prevailing in the international markets during that period and steep devaluation of the Indian rupee. The deceleration in growth after mid-1990s was also on account of the fall in international prices for most of the commodities and simultaneous steep increase in domestic administrative prices making Indian products noncompetitive.

An examination of trends in the exports of various commodities during recent years suggest that many commodities like rice, meat products, processed foods, fish, fruits and vegetables registered very high growth rates during the 1990s. On the other hand some traditional exports like tea and cotton were not able to sustain their growth rates after the liberalization. Marine products were the largest export earner while oil meals were also a major item in early 1990s. Recently oilmeal exports have suffered and cotton exports have collapsed. (Bhalla 2004).

Imports

India's agricultural imports have displayed extreme fluctuations, with a sudden surge in imports during the mid-1990s. In the post 1995-1996 period, the fluctuations in imports varied in the range of 58 % to 29 % (Table 4). The percentage share of agricultural imports in total imports also has shown very high volatility, having moved in the range of 28 % to less than 2 % during the same period. There was, in fact, a negative growth of 29 % in 2000-01 but since then, agricultural imports grew at a relatively high rate of about 23 %, 22 % and 27 % in 2001-02, 2002-03 and 2003-04, respectively. In recent years, imports of only two items, namely, pulses and edible oils have recorded consistently high volumes. Import of pulses, which used to vary in the range of 3-6 lakh tonnes in recent years except in 1997-98, when over 1 million tonnes was imported, surged to over 2 million tonnes in 2001-02 and has been close to that level since then, essentially reflecting

Table 4. India's imports of selected agricultural commodities 1990-91 to 2001-02 (million US$).

	1990-91	1991-92	1993-94	1994-95	1998-99	1999-00	2000-01	2001-02
Rice		4	18	3	0	6	3	2
Wheat		0	40	0	266	179	2	1
Cereals and prep	102	66	35	26	25	222	19	18
Pulses	268	121	186	199	322	82	109	663
Sugar	5	0	0	727	127	256	7	7
Fruits and nuts	41	41	69	100	155	136	176	158
Milk/cream	3	3	5	2	1	25	2	2
Cashew nuts	75	108	154	220	207	276	211	90
Crude rubber	126	74	109	118	160	143	152	174
Wool raw	102	80	119	112	161	114	100	131
Cotton raw	0	2	6	161	22	289	259	430
Jute raw	11	2	11	20	14	32	18	20
Vegetable oils	182	101	53	199	745	1,857	1,334	1,356
Pulp and paper	255	121	151	202	284	256	282	295
Agri. imports	915	598	805	1,884	3,292	3,432	2,388	3,049
Agri. exports	3,354	3,203	4,028	4,226	6,626	5,773	6,256	6,154
Total imports	24,075	19,411	23,306	28,654	41,484	49,671	50,536	51,413
Total exports	18,143	17,865	22,238	26,330	35,006	36,822	44,560	43,827

the shortage of domestic production. Similarly, import of edible oils surged from 1 million tonnes in 1995-96 to over 4 million tonnes in 1999-2000 and has since been moving in the range of 4.2 to 5.3 million tonnes per year, accounting for about half of domestic consumption. As in the case of agricultural export items, concerted efforts are required to raise the productivity and production of both pulses and oilseeds in the domestic sector.

Thus on balance, while after 1996 there was a deceleration in export growth, the agricultural imports have shown an increase. In fact the gap between agricultural exports and imports has been narrowing down in recent years. Although India abolished its quantitative restrictions (QRs) in 2001, this has not resulted in any surge of agricultural imports (Table 4). There is an increase in growth but this is mainly because of large imports of edible oils. Recently there has also been a sharp increase in the imports of cotton, raw wool and rubber.

India has a large potential to increase its agricultural exports in a liberalized world provided it can diversify a significant part of its agriculture into high-value crops and in agro-processing. This would depend first on undertaking large infrastructure investment in agricultural and agro-processing as also in rural infrastructure and research and development. India has not only to create export surplus but also to become competitive through increased efficiency of production in agriculture. The potential for exports would also depend on freeing of agricultural markets by the developed countries.

Agricultural Support Policies

India, like most of the other countries including developed countries, employs a variety of instruments to both protect and support its agriculture. These instruments can broadly be clubbed into three categories: domestic policies, import policies and export policies. The domestic policies comprise a wide range of policy instruments like input subsidies on fertilizers, power, irrigation water, public investment in development of water resources – surface and groundwater, government intervention in markets, direct payment to farmers (such as those in the form of deficiency payments, insurance and disaster payments, stabilization payments, and also some compensatory payments), price support for major crops , general services (such as government transfers to agricultural research and development, extension services, training and agricultural infrastructure etc.), other support (comprising such measures like certain tax concessions specific to agriculture or local or substantial level funding for agriculture etc.). Import policies refer essentially to border protection through trade barriers such as quantitative restrictions, quotas and tariffs on imports, which in the process create a wedge between domestic and world market prices. Export policies include those that either promote export (through instruments like subsidies and marketing arrangements that make exportables of a country more competitive) or those policies that constrain exports (often through canalization and restriction of exports and export taxes etc.). Usually, however, import policies are discussed in the context of trade policies rather than support to agriculture *per se*. Domestic support and export policies are often intermingled - export subsidies are more often than not a fallout of domestic support policies that maintain domestic prices of agricultural products within a country at levels higher than international prices. Of the different types of domestic support to agriculture, however, the most important have been through subsidization of input prices and subsidization through payment of higher prices of crop output than that would prevail in a free trade scenario.

Impact of Domestic Agricultural Support Policies

The measure of domestic support is often discussed in terms of two parameters - the Aggregate Measure of Support (AMS) and the Producer Support Estimate (PSE). In terms of both the measures, despite heavy input subsidies, the aggregate impact of the whole gamut of domestic support policies, when viewed in an international trading context, indicate that when all commodities were treated as imports, aggregate farm output was taxed by this policy regime during 1986-2002. Outlays on price support and input subsidies are large, but the impacts of these measures have typically been more than offset by relatively low domestic farm gate prices that prevail due to quantitative import and export restrictions and high marketing costs. More recent protection estimates show that through a combination of rising budgetary subsidies and smaller gaps between domestic and world prices, the taxation of Indian agriculture has declined significantly. When the major commodities are treated as exportables - and relative prices are compared at the border rather than the farm gate - protection even turns positive for 2001 and 2002 (Landes and Gulati 2004; Gulati and Narayanan 2003; Gulati and Kelly 1999).

WTO Agreements and Agriculture: An Overview and Current Status of Negotiations

After the Uruguay Round negotiations, agriculture trade is now firmly within the multilateral trading system. The WTO Agriculture Agreement, together with individual countries' commitments to reduce export subsidies, domestic support and import duties on agricultural products formed a significant first step towards reforming the agricultural trade.

The Uruguay Round agreement had set up a framework of rules and started reductions in protection and trade-distorting support. But this was only the first phase of the reform. Article 20 of the Agriculture Agreement committed members to start negotiations on continuing the reform at the end of 1999 (or beginning of 2000). Those negotiations, currently underway, began using Article 20 as their basis. The November 2001 Doha Ministerial Declaration set a new mandate by making the objectives more explicit, building on the work carried out thus far, and setting deadlines. The negotiations have been difficult because of the wide range of views and interests among member governments.

The prominent issues in the negotiations mandated under Article 20 have been referred to as a 'tripod' whose three legs are export subsidies, domestic support, and market access (more commonly called 'the three pillars' of agricultural trade reform). Non-trade concerns and special and differential treatment for developing countries would be taken into account as appropriate. The negotiations are now in their fifth year. Negotiators missed the March 31, 2003 deadline for producing numerical targets, formulas and other 'modalities' for countries' commitments. A revised draft 'modalities' paper was put up in March 2003 and although it was not agreed, it was used to discuss technical details in subsequent months. A number of 'framework' proposals dealing with main points of the modalities were submitted and discussed before and during the Fifth Ministerial Conference in Cancun, Mexico, September 2003, but it was not until August 1, 2004 that a 'framework' was agreed on. The next stage now is to agree on full 'modalities', which will in turn be used to work out the final agreement on revised rules, and individual countries' commitments. The Doha Declaration had envisaged that countries would submit comprehensive draft commitments, based on the ‘modalities’ by the Cancun Ministerial Conference — but without modalities, this target was not met either. Meanwhile, the final deadline for completing the negotiations, January 1, 2005, was officially postponed on August 1, 2004, without a new date set, though unofficially it was set for December 2006.

August 2004 Agreed Framework: Salient Features

On Domestic Support

All developed countries will make substantial reductions in distorting supports, and those with higher levels are to make deeper cuts from ‘bound’ rates (the actual levels of support could be lower than the bound levels). The way to achieve this will include reductions both in overall current ceilings (bound levels), and in two components — Amber Box and de minimis supports. The third component, Blue Box supports, will be capped; at the moment the Blue Box has no limits. The fine print contains a number of details but also stresses that these have to meet the long-term objective of ‘substantial reductions’.

All of these reduction commitments and caps will apply. However, the new WTO ceiling at the end of the implementation period will be the lower of the value of trade-distorting support resulting from (i) the overall cut and (ii) the sum of the reductions/caps of the three components. In other words, countries would have to make the required reductions in Amber Box and de minimis support, and be within the capped limit of the Blue Box. Then, if they are still above the overall limit, they will have to make additional cuts in at least one of the three components in order to match the ceiling set by the overall cut.

Developing countries will be allowed gentler cuts over longer periods, and will continue to be allowed exemptions under Article 6.2 of the Agriculture Agreement (they can give investment and input subsidies that are generally available and are integral parts of development programs, and provide domestic support to help farmers shift away from producing illicit crops).

On Export Subsidies and Competition:

The framework states clearly that all forms of export subsidies will be eliminated by a ‘credible’ date. The elimination will work in parallel for all types of subsidies, including those in government-supported export credit, food aid, and state-sanctioned exporting monopolies. The negotiations will also develop disciplines on all export measures whose effects are equivalent to subsidies.

On Market Access

The framework commits members to ‘substantial improvements in market access for all products’. Three or four key points emerged in the bargaining over the framework: the type of tariff reduction formula that would produce the agreed result of ‘substantial improvements in market access’; how all countries’ sensitive products might be treated; how developing countries might be given further flexibility for their ‘special products’ and be able to use ‘special safeguard’ actions to deal with surges in imports or falls in prices; how to deal with conflicting interests among developing countries over preferential access to developed countries’ markets; and how to provide market access for tropical products and crops grown as alternatives to illicit narcotics. Also discussed was a possible trade-off between cuts in some developed countries’ subsidies and improved market access in developing countries.

WTO Negotiations on Agriculture: India's Stand

India has been active in WTO negotiations both as a sovereign nation and also collectively as a principal member of G20 and G33 groups of nations. While conforming to the substance of framework agreement these countries have emphasized that the reforms in all three pillars form an interconnected whole and must be approached in a balanced and equitable manner. These countries have individually and collectively suggested:

On Domestic Support

In order to fulfill the mandate of 'substantial reductions in trade-distorting domestic support', negotiations should determine base periods and initial and final numbers for the overall trade-distorting domestic support in a technically consistent and politically credible manner. Any change in the Blue Box (Article 6.5 of the Agreement on Agriculture) is contingent upon agreement on additional criteria in order to make it substantially less trade-distorting than it is now. It should be ensured that in the Green Box no, or at most minimal, trade-distorting effects or effects on production will be generated by any direct payments claimed to be exempt from reduction commitments. Green Box should be reviewed and clarified to include specific provisions designed to accommodate genuine agriculture and rural development program of developing countries aimed at alleviating poverty, promoting agrarian reform and settlement policies, and ensuring food security and addressing livelihood security needs. Further, for facilitating implementation of Green Box measures in developing countries, their special circumstances would also need to be taken into account. Further, given that de minimis support is the only form of support available to farmers in most developing countries, any attempt to reduce de minimis support in developing countries would negatively affect the programs benefiting subsistence and resource poor farmers.

On Export Competition

In the export competition pillar, a key decision to be taken is the date of elimination of all forms of export subsidies. They have urged countries that apply such instruments to eliminate them in a period no longer than 5 years and with a front-loading of commitments. An early agreement would inject new momentum to the agriculture negotiations and make progress easier in other fronts. They stressed the need to develop new disciplines on export credits, export credit guarantees and insurance programs and food aid so that these instruments are not used so as to displace exports or to promote surplus disposal. They have also recalled the need for making operative the 'July Framework' provisions for special and differential treatment including State Trading Enterprises and the concerns of Net Food Importing Developing Countries (NFIDCs) as provided in the Marrakesh Decision.

On Market Access

On market access, the crucial importance of conversion into ad valorem equivalents (AVEs) for the completion of the core modality – the tariff reduction formula has been emphasized. The treatment of non-ad valorem (NAVs) duties should clearly spell out the methodologies used for conversion so that the verification process does not become cumbersome. The long held view that the tariff reduction formula is the main component of the market access pillar and should be negotiated before addressing the issue of flexibilities has been reaffirmed. It has been underlined that the tariff reduction formula must contain: (i) progressiveness – deeper cuts to higher bound tariffs; (ii) proportionality – developing countries making lesser reduction commitments than developed countries and neutrality in respect of tariff structures; and (iii) flexibility – to take account of the sensitive nature of some products without undermining the overall objective of the reduction formula and ensuring substantial improvement in market access for all products. It has been strongly stressed that special and differential treatment for developing countries must constitute an integral part of all elements with a view to preserving food security, rural development and livelihood concerns of millions of people that depend on the agriculture sector. The concepts of Special Products and Special Safeguard Mechanism are integral elements of special and differential treatment for developing countries. The elimination of tariff escalation is important for developing countries, as it would allow them to diversify and increase their export revenues by adding value to their agricultural production. A serious concern about the increasing use of Non-Tariff Barriers by developed countries, which acts as impediments to the exports of products of interest to developing countries, has also been raised.

Globalization and Domestic Policy Reforms

The importance of domestic reforms in an environment of increased global integration has been widely acknowledged. It has been asserted that large-scale welfare gains from multilateral agricultural liberalization are contingent on well-functioning domestic economies and that if factor markets were inflexible or public infrastructures were in poor shape only a fraction of the gains from trade reforms would be realized (Anderson 2003). The Reserve Bank of India (RBI) observed in its 2001 Annual Report that "…the pace of progress in liberalization of external trade in agriculture warrants a sense of urgency and priority to institutional reform in agriculture."(RBI 2001). While stressing the importance of public investment in basic infrastructure the RBI stressed the importance of effective supply chain arrangements that encompassed storage, processing and trading. It also noted a major concern of regulating intermediaries. There is a strong perception that inadequate regulation of intermediaries in agricultural trade acutely affects farmers on account of low farm gate prices. Policy constraints such as restrictions on movement of agricultural commodities and *ad hocism* in export policy have been cited as a major source of regulatory problems (Government of Kerala 2003). The Government of India removed several statutory restrictions in its 2002 National Agricultural Policy. In early 2004 the government liberalized procurement of food grains for the export market; exporters are now permitted to procure rice and wheat from farmers at market-determined rates. Food grain market policy in India has tended to be highly interventionist with the central and state governments actively involved in grain storage and restrictions on the movement of food grains across states (Jha and Srinivasan 2004). Transport costs are also extremely high in India. It has been estimated that comprehensive reform and infrastructure intervention consisting of rationalization of internal movement controls, reduction of transport costs by 50 % and decentralization of public procurement and the PDS would have the effect of increasing welfare by about US$2 billion. The efficacy of India's Public Distribution System (PDS) in ensuring food security to the poor has been a subject of extensive criticism. Implementation of modified PDS programs, such as the targeted public distribution system (TPDS), has also proven difficult in India as a result of weak administrative capacity and resource constraints at the local level. The Planning Commission's mid-term review acknowledges that the minimum support policy (MSP) policy has been ineffective, farm incomes declined in regions subject to the MSP, and in 2001 it was decided to lower stocks by lowering sales prices and increasing food for work. Nearly a third of the growth in the unirrigated regions since the mid-1990s has been through crop diversification, especially to horticultural products. Support price policy, particularly for wheat and rice, has remained delinked from domestic and international market realities, creating significant budgetary costs and market distortion. Although initial upward adjustments in domestic prices may have been justified due to the prevailing negative support to cereals, policy was unable to adjust with market conditions. The inability to reform price policy and certain input subsidies has led to a decline in public investment in agriculture at a time when investment in new infrastructure and institutions is needed. Although the incentives and climate for private investment have improved, it may not be able to fully substitute for weak public investment. Reforms at the border, when they have been implemented, have typically exposed inefficiencies in the domestic market that limit competitiveness. These weaknesses limit the benefits of border reform and, at least in India's case, will require significant investment in transport and marketing infrastructure and institutional capacities to overcome.

As a result of commitments under the Uruguay Round, India has bound all the tariff lines in agriculture. India had bound its tariffs at 100 % for primary products, 150 % for processed products and 300 % for edible oils, except for certain items (comprising about 119 tariff lines), which were historically bound at a lower level in the earlier negotiations. The applied rates have been much lower than the bound rates. In India the product-specific support is negative, while the non-product specific support i.e., subsidies on agricultural inputs, such as power, irrigation and fertilizers is well below the permissible level of 10 % of the value of agricultural output. Therefore, India is under no obligation to reduce domestic support currently extended to the agricultural sector. Export subsidies of the kind listed in the Agreement on Agriculture, which attract reduction commitments, are not extended in India. Also, developing countries are free to provide certain subsidies, such as for export marketing costs, internal and international transport and freight charges etc.

India: Effects of Past Liberalization

Trade liberalization primarily causes changes in producer and consumer surplus and the net effects of this liberalization depend on which of the two effects is stronger. Several researchers have attempted to quantify the effects of trade liberalization. The available results point to mixed evidence of the effects of trade liberalization. A study by Ramesh Chand 1999 attempted to quantify the impact of globalization of agriculture on producer surplus, consumer surplus and net social welfare in the case of four crops, namely, paddy (rice), maize, chickpea and rapeseed-mustard. The study concluded that in the case of studied crops, free trade is likely to have sharp positive impact on net return from production of exportables like maize and rice, whereas, it is likely to have small negative impact on net return from the importables like rapeseed-mustard. In rice where level of input subsidy is high, free trade would not be sufficient to counter the adverse impact on income due to withdrawal of subsidies.

In a recent study Jayati Ghosh, examined the impact and policies strategies with special reference to India, however, opined that more liberal external trade has not, in general, had a beneficial impact on cultivators in India. This has been partly because of the patterns in world trade which have led to volatile and declining crop prices internationally. But it also has a great deal to do with internal macroeconomic and sectoral policies which have reduced protection to cultivators, caused input prices to rise sharply, made marketing of crops more difficult and exploitative for the direct producers and reduced the flow of institutional credit. The critical question, therefore, in the current context is how to manage trade liberalization and domestic policies so as to ensure the viability of small cultivators and food security in the countryside.

In some products, such as edible oils, international prices on account of subsidies have consistently been lower than domestic prices. Analysts addressing this issue have consistently shown that Indian edible oils do not compete well with imports (Gulati and Sharma 1998). Comparing the ratio of domestic and international prices of oilseeds and oil, Chand 2002 shows that oilseed production, particularly in rapeseed-mustard and soybean, is fairly competitive. This is also shown by a World Bank 1997 study. It is in oils that India is on shaky grounds (Chand 2002). Inefficiencies in the oil-processing sector is one reason; the other factor is the subsidy-driven ability of foreign producers to sell cheap oil. These and other findings indicate that oilseed production in the country faces a threat due to inefficiency of processing and marketing and also due to the transmission of volatility in world prices to the domestic market. India liberalized its, soybean and soy oil import policy in August 1999. This led to dumping of subsidized imports of soybeans on the Indian market. These imports totaled 3 million tonnes in one year (a 60 % rise compared to earlier years) and cost nearly US$1 billion. Within one growing season, prices crashed by more than two-thirds, and millions of oilseed-producing farmers had lost their market, unable even to recover what they had spent on cultivation. While the declining prices have hurt producers, consumers have gained considerably. This would require the government to balance the competing interests of producers and consumers and perhaps lean towards poor and small-scale producers (Chand et al 2004). In another study on oilseeds, as a result of successive lowering of tariffs on edible oils – first from 65 to 30 %, and then to 15 % in 1998- and lifting of non-tariff restrictions, imports soared, and India went full circle from self-sufficiency to the world's largest importer in only 5 years. As a result of which, thousands of Indian farmers lost their livelihoods (Mark Fried 2004).

In the case of pulses, Sathe and Agarwal 2004 examined the issues related to the opening up of the Indian pulses sector. The study shows that pulses (lentils) imports have not augmented supply to such an extent that there would be a strong, negative relationship between prices and imports of pulses. Though the import duties on pulses have been generally low the result of our import regime has been such that it has not depressed prices in a substantial way.

Liberalization of imports may have a negative effect on the Indian agrarian economy mainly on account of the huge subsidization of agriculture by most of the developed countries, which implies that imports are sold below the cost of production in India, the imperfect nature of world agricultural markets and also on account of higher volatility of agricultural prices in international markets which in turn gets transmitted to the domestic markets.

A study by Sekhar 2004 attempts to assess the implications for food security of the poor through transmission of international price volatility into domestic markets which arises on account of globalization in agriculture. The commodities selected for study are wheat, rice, groundnut oil, soybean oil, coconut oil, sugar, cotton and coffee. His study shows that extreme volatility in commodity prices, particularly of food commodities, adversely affects poor agricultural laborers and those engaged in the unorganized sector because their wages are not index-linked. For exporters, price volatility increases cash-flow variability and reduces collateral value of inventories. In order to understand the implications of trade liberalization, particularly import liberalization, it is essential to examine the long-term movements of domestic and international prices and assess the degree of divergence between the two. A price wedge – percentage difference between the monthly domestic and international prices for 10 years since 1990 – has been calculated for this purpose. His study shows that where bound tariffs are much higher than the observed price wedges, the bound rates may be lowered. He concludes by stating that as short-term variability in agricultural prices in international markets is not found to be higher than domestic markets in India, international trade may be used as a short-term price stabilization strategy in case of supply shocks. At the same time, care should be taken to negotiate appropriate tariff bindings to protect against cheap imports resulting from unfair subsidization in some developed countries.

Potential Impacts of Liberalization

Estimating the potential impacts of liberalization of trade in agricultural and non agricultural commodities in the wake of WTO negotiations on agriculture is complicated and would depend on the outcome of the negotiations currently underway. More specifically it would in large part depend upon the extent to which the developed countries are willing to scale down their domestic support, export subsidies, tariffs, and non-tariff barriers and let increase their market access for the developing and least developed countries. While several proposals are currently on the table in respect of each of these components, agreements have alluded all of them. Several researchers have nevertheless attempted to evaluate, using the scenario analysis approach, the likely impacts of some of the alternative proposals under discussion in one or more of these areas on one or more of the affected variables viz international prices, production, trade and welfare at the global and /or at the level of a region/country. In the following paragraphs we attempt to very briefly give a summary of impacts from a few of the selected recent studies on the subject. It may, however, be important to mention that the results obtained from different studies are not strictly comparable because of the differences in underlying assumptions, the differences in methodology employed, the time frame considered and the nature of impacts analyzed. The results from most of the studies on liberalization of agricultural trade point towards an increase in international prices of a majority of the agricultural commodities, increase in volume of international trade and an increased welfare consequent upon liberalization. The impacts on production of different crops, principally the cereals, however, appear to be marginal.

USDA 2001 has estimated that the full elimination of global agricultural policy distortions would result in an annual world welfare gain of US$56 billion. Moreover, elimination of agricultural trade and domestic policy distortions could raise world agricultural prices by about 12 %. Evaluating the impacts of comprehensive multilateral liberalization of agricultural trade policies using a CGE model, Cline estimates that the welfare benefits from a free trade in agriculture for India will be to the tune of U$0.82 billion. Full liberalization of OECD farm policies would boost the volume of global agricultural trade by more than 50 % but would cause real food prices to rise by only 5 % on average (Anderson, 2003). Some models have projected food price rises of about 8 - 12 % (Diao et al. 2002). Another study (Beghin and Aksoy 2003) estimate that world prices are likely to go up by even higher margins:

10-20 % for cotton, 20-40 % for dairy products, 10-20 % for groundnuts, 33-90 % for rice and 20-40 % for sugar. Results of a World Bank study indicate that a removal of agricultural tariffs and subsidies by all WTO countries would generate an increase in developing country exports of 15 % and increase in imports of 12 %. In terms of this study, India would experience an increase in exports of 13 %. World prices of wheat are expected to rise by about 10 % and prices of rice are expected to rise by about 16 %. As a net exporter of both rice and wheat, India, therefore, stands to gain significantly from terms-of-trade improvements.

Babcock et al. 2003 using the FAPRI model have analyzed the impact of liberalizing agricultural markets on world trade flows, prices and market equilibrium. The analysis has been carried out under two possible scenarios - the full trade liberalization scenario and trade-only liberalization scenario. The results obtained suggest that under a full liberalization scenario, the world wheat, rice and cotton prices are estimated to go up by 4.8 %, 10.3 % and 15 %, respectively. Under the trade-only liberalization scenario the corresponding increase in the prices of wheat, rice and cotton are likely to be of the order of 7.6, 10.6 and 3 %, respectively. Because of the removal of export subsidies Indian exports of wheat are estimated to decrease under the full liberalization scenario and India is projected to become a net importer by 2003/04 with trade only scenario. Rice trade increases by 29 % under the full trade scenario and by about 27 % in the trade-only scenario. Most of these exports are captured by China, India and Vietnam followed by Thailand. On an average Indian exports of rice are estimated to grow by over 100 % under the full liberalization and by 56 % under the trade-only scenario. In the case of cotton, under the full liberalization scenario net cotton imports decline by 16 %. In the trade only scenario Indian exports of cotton increase by just 2 %. Thus India is likely to gain much more in the rice and cotton sectors under a scenario of full liberalization. The present exercise, however, does not take in to account the transportation cost when estimating the flow of trade. In the case of wheat, the transportation cost vis-à-vis the US is relatively high, and India is likely to have an advantage when competing with the US in export destinations closer to the former even after elimination of export subsidies.

Evaluating the implications of some of the alternative tariff reduction structures, a study by Vanzetti and Peters 2003 using general equilibrium models, shows that the one tariff-harmonizing Swiss formula component with rather ambitious coefficients of 25 for developed and 50 for developing countries gives overall welfare effects that are not much higher than a continuation of the Uruguay Round approach. Assuming reduction in export subsides by 45 % and domestic support by 55 % further reduces the global welfare gains.

Another recent World Bank study shows that in terms of potential reform, or the pillars of agriculture negotiations, increased agricultural market access is the key to successful liberalization of merchandise trade, accounting for well over half the potential economic welfare gains to developing countries and the world as a whole from removing all merchandise trade distortions and farm subsidies. Within agriculture, the potential gains from market access are shown to be far more important than those from abolition of domestic support and export subsidies, accounting for 93 % of the gains from total agricultural liberalization (Anderson 2003).

Another study demonstrates how improving market access in the developed countries through lowering of tariffs would be beneficial to India. Domestic support has been viewed as the equivalent of implicitly imposing tariffs. Cline 2003 has estimated the tariff equivalent of all subsidies and added it to tariff rates in the Quad (US, EU, Japan, Canada) to indicate the overall levels of protection provided by the Quad to agriculture. Thus in the case of EU and US if tariff equivalents of subsidies are taken into account the overall tariff protection rises substantially. Using this approach, it is suggested that unless domestic support is reduced the real tariff reduction effects for India would be only two- thirds of the total gain. This would be particularly the case for the US and the EU whose tariff equivalent of subsidies is far greater than for other countries. In fact, 'tariffication' of the level of subsidies and adding it to the tariff rates is a far more logical way of addressing the effects of subsidies than through notifications of subsidies and targeting reduction commitments on these notifications.

Anderson 2003 has projected that a complete global liberalization of agricultural trade (including the removal of massive agricultural protection by OECD countries) would have the effect of increasing net annual exports of agricultural and food products by US$2.7 billion from India: a 40 % rise over the current level of agricultural exports. The current annual value of agricultural production in India is close to US$100 billion. A US$2.7 billion growth in exports would constitute in itself close to 2.7 % annual growth in value of Gross Domestic Agricultural Product, which equals the current average annual growth rate. This is based on the assumption that all additional exports come from additional domestic agricultural production and is not diverted from domestic consumption**.** Thus assuming an adequate supply response, growth rates in agriculture production may tend to double on average for the first few years.

UNCTAD using a GTAP - CGE model, has attempted to evaluate the impacts of twoagricultural tariff reduction scenarios (1) 3 large band approach I-soft tariff reduction; and (2) 3 small band approach I- hard tariff reduction, on imports, exports, production and welfare in India (UNCTAD 2005). The results obtained suggest that while welfare improves with tariff cuts in the hard scenario the same is not true for other variables. Developed countries as a whole see much larger gains in the soft scenario in comparison with the hard scenario (Table 5). Some products emerge as being sensitive on several counts. Paddy sees a decline in output and employment in the soft scenario, but both exports and imports increase under both scenarios. However, the extent of import increase, from a smaller base, is much larger than the extent of export increase. The study thus suggests that paddy and rice trade should be liberalized cautiously. Vegetables, nuts and fruits also show an output and employment decrease along with an increase in trade. Oilseeds and oil show an output and employment decline accompanied by import increases and minor export increase.

In another major study to analyze the implications of selected scenarios in all the three pillars of agricultural negotiations, UNCTAD using partial equilibrium modeling employed Agricultural Trade Policy Simulation Model (ATPSM) to assess the implications of tariff cuts, export subsidy cut, and domestic subsidy cut on Indian agriculture (UNCTAD 2005).

Table 5. Impact on welfare: welfare gains (in million US$).

EV	Soft	Hard
India	210.93	331.05
Developed countries	2,036.05	22.11
Developing countries	752.34	42.74
Least developing countries	18.37	4.95

For evaluating the implication of tariff cut, four scenarios were formulated – continuation of Uruguay Round Formula, three band soft approach, three band hard approach and four band hard approach (Table 6). Comparing all the four simulations at an overall level it is easy to observe that the total welfare is highest in the third scenario, which is a hard scenario. However, export and import growth is higher in the case of the four-band simulation. The study suggests that for India the negotiating strategy should be based on maximizing the producer surplus, as the producers of agriculture are generally poor and a pro poor strategy would imply a maximization of the producer surplus. However, it is also to be noted that poor urban consumers are likely to be hit by tariff changes. On balance, however, as a larger share of total population is dependent on agriculture, maximizing producer surplus may be a priority-negotiating objective. On this basis the Uruguay Round Formula or the four-band formula may be the right approach to adopt.

Table 6. Change in key agricultural trade, production and welfare indices for India.

	UR formula	3 band soft	3 band hard	4 band hard
Production (% change)	1.266	1.180	1.333	2.082
Imports (% change)	7.76	6.44	13.90	8.87
Exports (% change)	67.92	62.20	90.14	103.17
Consumer surplus (million USD)	-948	-909	-766	-1,642
Producer surplus (million USD)	970	920	825	1,696
Total welfare (million USD)	73	55	139	112

The change in volume of agricultural production sees the most favorable effect under the Uruguay Round scenario, and what is interesting to observe is that production would increase in response to tariff liberalization in all scenarios except in the four band scenario (Table 7). The distribution of gains in output, however, favors cash crops such as cotton, sugar, tropical fruits, vegetables, roots and tubers, meats and staple grains such as rice and wheat. These would respond favorably to market access gains in other countries. The decline in production can be seen in hides and skins (which in any case has 0 tariffs), coarse grains, milk and livestock. This may indicate substitution in the consumption basket for coarse grains with other grains, as well as import surges in those items thus reducing production. The overall gains on an average in most products can be observed in the UR scenario.

For evaluating the impact of cut in export subsidies by developed countries, partial equilibrium modeling – ATPSM was employed. The simulations involving ATPSM involve eliminating export subsidies given by developed countries – the US, EU, Canada and Norway for agricultural products. The results (Table 8) show that on elimination of export subsidies, India's imports increase by approximately 0.2 % and exports by 12% %. Exports increase mainly in livestock, meat products, butter, barley, tomatoes, apples and sugar. Production increases by 0.1 % and consumption falls by 0.1 %. Welfare for India increases by 12 million dollars. Producer surplus increases by US$375 million and consumer surplus falls by about US$362 million. Government revenue increases by a negligible percentage.

Table 7. Change in production.

	Based on volume change				Based on value of production change			
Product	UR formula	3 band soft	3 band hard	4 band hard	UR formula	3 band soft	3 band hard	4 band hard
Livestock	-1.37	-1.10	-2.40	-1.70	-7.4	-6.2	-12.5	-9.2
Bovinemeat	0.20	0.15	0.25	0.15	2.3	1.9	13.3	1.9
Sheepmeat	1.28	1.20	2.15	1.75	3.8	4.0	6.7	6.0
Pigmeat	0.53	0.48	0.96	0.75	2.4	2.2	4.2	3.3
Poultry	0.63	0.51	1.03	0.66	2.4	1.9	3.9	2.5
Milk, conc.	-3.04	-3.11	-2.41	-4.03	-0.2	0.6	5.3	0.7
Butter	0.12	0.12	0.06	0.15	4.7	5.0	3.7	6.4
Cheese	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A
Wheat	1.02	0.62	1.21	1.64	4.2	2.6	5.1	6.9
Rice	0.37	0.44	0.43	0.75	1.5	1.7	1.8	3.0
Barley	-6.77	-5.22	-8.47	-11.92	-6.7	-5.0	-7.9	-11.6
Maize	-0.15	-0.06	0.19	-0.14	0.6	0.7	2.0	1.6
Sorghum	-1.12	-0.94	-1.24	-1.71	-2.4	-1.9	-2.4	-3.2
Pulses	0.32	0.45	0.54	0.34	1.1	1.6	2.1	1.2
Tomatoes	1.74	1.14	2.03	0.74	3.2	2.1	3.8	1.4
Roots and tubers	0.48	0.31	0.57	0.41	2.1	1.3	2.5	1.8
Apples	1.02	0.63	-1.61	0.65	2.9	1.8	-4.5	1.8
Citrus fruits	1.51	1.00	1.60	1.18	2.6	1.7	2.8	2.0
Bananas	0.00	0.00	0.00	0.00	N/A	N/A	N/A	N/A
Other tropical fruits	0.45	0.36	0.39	0.52	1.4	1.1	1.4	1.6
Sugar, raw	1.09	1.05	1.45	1.98	2.5	2.3	3.2	4.5
Sugar, refined	1.29	1.39	2.25	2.33	3.7	3.9	6.5	6.7
Coffee, green	0.04	0.04	0.09	0.06	0.1	0.1	0.5	0.3
Coffee, proc.	0.36	0.24	0.27	0.25	0.6	0.4	0.7	0.4
Cocoa beans	0.02	0.02	0.02	0.02	0.0	0.0	2.9	0.0
Cocoa, proc.	0.20	0.12	0.12	0.12	0.9	0.5	13.5	0.5
Tea	0.21	0.20	0.39	0.42	1.0	1.0	2.2	2.0
Tobacco leaves	0.29	0.22	0.41	0.51	1.7	1.3	2.5	3.1
Hides and skins	-0.59	-0.69	-1.23	-1.18	0.4	0.2	-0.3	-0.4
Oilseeds, temp.	0.43	0.31	0.66	0.60	2.4	2.0	4.1	3.1
Oilseeds, trop.	0.31	0.31	0.37	0.35	1.8	1.9	2.7	1.9
Rubber	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
Cotton	0.52	0.43	0.43	0.64	1.7	1.4	1.6	2.1
Vegetable oils	0.07	0.02	-0.04	0.18	1.1	0.8	2.5	1.9
Average of volume changes	0.04	0.02	0.01	-0.10	1.3	1.2	1.3	2.1

Table 8. Export and domestic subsidy cut simulation results: impact on production of select commodities.

Commodity	% Change in production due to	
	Export subsidy cut	Domestic subsidy cut
Wheat	0.18	0
Rice	-0.003	0.01
Barley	0.88	-.01
Maize	-0.27	0.003
Pulses	0.0006	0
Cotton	0	0
Raw sugar	0.18	0
Total (all commodities including those not listed above)	0.12	0.001

Partial equilibrium modeling - ATPSM was also employed for evaluating the impact of cut in domestic subsidy. Domestic support expenditure is reported for four countries - EU (US$31 bn), US (US$5 bn), Japan (US$4 bn) and Republic of Korea (US$8 bn). The expenditure is mainly on bovine meat, pig meat, dairy products, cereals, sugar and oilseed. A cut in domestic support under a specified formula (domestic support cut in the following manner: >US$25 bn, 20 % cut, US$12-US$25, 10 % cut, US$2-US$12, 5 % cut and <US$2, 5 % cut) leads to an export increase of 0.15 %. Export increases are registered mainly in livestock (210 %), butter (40 %), sugar (16 %) and poultry (10 %). Barley and sorghum register falls in exports. This could be because other countries are more competitive producers. Production increases by a negligible percentage of 0.001 % (Table 8). Consumption reduces by 0.002 %. Total welfare improves by a marginal 0.3 million dollars; with government revenue increasing by a small proportion and a positive producer surplus and negative consumer surplus. However, it is to be noted that domestic support only includes AMS cuts, not blue box or de-minimum and, hence, does not provide a comprehensive picture of the total support which may be subject to reduction commitments. It also does not include product-specific caps which would further limit the extent of subsidy. This is why the effects of reductions in domestic support would be minimal.

A comparison of the relative impacts of alternative scenarios analyzed in a partial equilibrium framework indicate that cuts in tariffs would yield higher gains overall for India, rather than domestic support and export subsidy cuts. Moreover, the deeper the tariff cuts the higher are the gains. However, if the number of tariff bands are increased, even with deeper tariff cuts, India’s gains would decrease. Asymmetric across the board cuts of the Uruguay Round would yield the most significant gains for India in terms of several parameters, but export gains are modest, and the losses would also be lower than in the three or four band formula. The effects of reduction in domestic subsidy are much lower than the effects of reduction in export subsidy. Thus India should target a negotiating strategy preferably with Uruguay Round cuts. However, if that were not possible, then fewer bands with deeper progressive cuts would be better for India. However, the welfare gains of tariff liberalization along with domestic subsidy and export subsidy reductions are very significant.

In another comprehensive study on evaluating the impact of two agricultural trade liberalization proposals viz the Swiss Formula and Uruguay Round on India, Kirit Parikh 2004 employed a sequential applied general equilibrium model laying particular emphasis on the impact on welfare. The model has a rich policy structure and provides for tariff policy, trade quotas, stock policy, tax policy and redistributive policy. The alternative scenarios analyzed are: SAM–Reference Scenario (which reproduces the base year SAM as a solution for the year 1997 when the run is with actual 1997 tariffs), FTR- Free Trade Uruguay Round with 50 % cut (all agricultural tariffs cut by 50 %, this is the Uruguay round scenario), and FS1 – Swiss Formulae with c = 1. In all the scenarios, the world market prices are kept the same. The scenarios thus reflect a unilateral liberalization by India and also assume that India's trade has little impact on world prices. All the scenarios are run for 4 years starting 1997. The policy changes are introduced in 1998. The impacts on agricultural prices are thus visible only in 1998 and the impacts on output are seen only in 1999 as agricultural output comes with a one-year lag. The simulations show that the welfare impacts are not unambiguous and neither of the two policies can be shown to be superior to the reference policy. It does, however, indicate that after a couple of years, greater trade liberalization is beneficial for a large number of persons indicating that with some safety net policy such as employment guarantee scheme, one may be able to get a win-win outcome.

In general, thus, if the prices of agricultural commodities like rice, cotton, wheat and sugar were to rise, India could generally improve its exports. Developing countries and the agricultural market in general stand to gain major benefits of reducing and eliminating subsidies and domestic support. It is, however, necessary to emphasize that this is only a general equilibrium picture and might be slightly more optimistic than reality,[2] as certain products of particular interest to India are likely to be liberalized least and there are other competitors who will, because of high trade logistic costs in India, rush to fill the breach.

Will India Be Able to Make Use of the Opportunities: Supply Side Scenario

Various analyses of some of the proposals under discussion at the WTO show that in overall terms India stands to gain from liberalization of trade in agriculture. However, given the recent trend of a slowdown in the growth of agricultural production and increasing domestic demand, will India be able to encash on the opportunities that may be made available to it by a more liberalized trade regime?

The recent mid-term appraisal of the 10th Five-Year Plan, commenting on the supply side scenario notes that agricultural growth has been poor, with productivity growth coming to almost a complete halt in several products. Within the crop sector only fruits, vegetables,

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[2] Critics also point to the many limitations of CGE models and the estimates they generate, and question the extent to which they should be informing trade policy at all.

condiments and spices have grown by over 2.5 % per annum. Output prices have fallen relative to input prices reflecting a fall in profitability in agriculture. On the demand side per capita consumption of all cereals, pulses and edible oils have fallen, with the growth of consumption decelerating for all types of food including milk, vegetables and fruit. This situation implies that there may be a need to focus on production and demand, increasing the scope of the provision of subsidies, through minimum support price in other areas such as the eastern region. Rao 2005, however, opines that the prospects for exports of food grains from India seem real, at least for a decade, if the growth rate in food grains output of around 3 % can be achieved, as the domestic demand for food grains is unlikely to exceed 2.6 % per annum with even 7 % growth rate in GDP. India is unlikely to absorb domestically the whole of food grains output from a growth rate of around 3 % for quite sometimes unless drastic changes in income distribution can be effected.

Conclusion

The evidence available from a number of research studies carried out to ascertain the likely impact of trade liberalization on the Indian agricultural sector suggests mixed results depending upon the assumptions made in the model employed to analyze and the extent to which developed countries cut their subsidies. On balance, the results tend to indicate that India's agricultural markets in general stand to gain from liberalization and derive benefits of reduction in subsidies and domestic support by developed countries. To enable India realize these gains it will need to increase its agricultural production through a step up in crop productivity, which has of late been showing the trend of a slowdown.

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Converting Rain into Grain: Opportunities for Realizing the Potential of Rain-fed Agriculture in India

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Introduction

India ranks first among the rain-fed agriculture practicing countries of the world both in terms of extent (86 M ha) and value of the produce. Due to low opportunities and higher population of landless households and agricultural laborers as well as low land and labor productivity, poverty is concentrated in rain-fed regions (Singh 2001). Yield gap analyses, undertaken by Comprehensive Assessment of Water in Agriculture (CA 2007) for major rain-fed crops found farmer's yield being a factor 2-4 times lower than achievable yields for major rain-fed crops. Grain yield oscillates around 1-2 t/ha compared with attainable yields of over 4-5 t/ha (Falkenmark and Rockstrom1993). The large yield gap between attainable yields and farmers' practice as well as between attainable and potential yields shows that a large potential of rain-fed agriculture remains to be tapped.

Rainfall is a truly random factor in the rain-fed production system and its variation and intensity is high in areas of low rainfall. Semi-arid regions, however, may receive enough annual rainfall to support crops but it is distributed so unevenly in time or space that rain-fed agriculture becomes unviable (Reij et al. 1988). Rockstrom and Falkenmark 2000 note that due to the high rainfall variation, a decrease of one standard deviation from the mean annual rainfall often leads to the complete loss of crop. Agricultural droughts, where primarily a skewed distribution of rainfall causes drought in the root zone, are more frequent than the real meteorological droughts. Dry spells (or monsoon breaks), which generally are 2-4 weeks of no rainfall during critical stages of plant growth causing partial or complete crop failures, often occur every cropping season. Therefore, besides several other factors related to agriculture sector as a whole, adverse meteorological conditions resulting in long dry spells and droughts, unseasonal rains and extended moisture stress periods with no mechanisms for storing and conserving the surplus rain to tide over the scarcity/ deficit periods were identified as the major cause for non-remunerative yields and heightened distress in rain-fed regions (Kanwar 1999).

Supplemental (or deficit) irrigation is a key strategy, so far underutilized on a regional basis, to unlock rain-fed yield potentials. Supplemental irrigation to bridge dry spells in rain-fed agriculture has the potential of increasing yields and minimizing risks for rain induced yield loss.

The existing evidence indicates that supplemental irrigation ranging from 50-200 mm/ season (500-2,000 m3/ha) is sufficient to mediate yield reducing dry spells in most years and rain-fed systems, and thereby stabilize and optimize yield levels (Wani and Ramakishna 2005). Since irrigation water productivity is much higher when used conjunctively with rainwater (supplemental), it is logical that under limited water resources priority in water allocation may be given to supplementary irrigation (Agarwal 2000; Joshi et al. 2005). Collecting small amounts using limited macro-catchments, water harvesting during rainy season in the potential regions/ districts can achieve this. Under the 'Strategic Analyses of India's National River Linking Project', a study was, therefore, made to estimate the available runoff in the potential regions to mitigate the terminal drought in the dominant rain-fed districts of India. The study developed a criterion and identified the dominant rain-fed districts for major rain-fed crops in India, made an assessment of the surplus runoff available for water harvesting and supplemental irrigation in these districts, estimated the regional water use efficiency and increase in production due to supplemental irrigation for different crops across the dominant districts and made a preliminary estimate of the economics of the proposed intervention. The next sections of the paper describe in brief the methodology and assumptions; and results and conclusions of the study.

Identification of Dominant Rain-fed Districts

A district (with an average size of ~ 0.5 M ha) is identified as the administrative and planning unit in India and all data sets pertaining to agriculture, water resources, climate, human development and related parameters are available for the district; so, 'district' was considered as unit of analysis for this research. Rain-fed crops in varying proportions are cultivated throughout the rural landscape of the country. The earlier classifications of rain-fed areas were based on fixed or variable percentages of irrigated area (Kerr et al. 1996) in the district irrespective of the area under major rain-fed crops. An improved criterion for the identification of rain-fed districts for a given crop was based on the total rain-fed area under the crop in the district (CRIDA 1998). For the present analysis, districts in the descending order of area coverage limiting to cumulative 85 % of total rain-fed area for each crop were identified and termed as 'dominant rain-fed districts' for a given crop. Crops covered were sunflower, soybean, rapeseed mustard, groundnut, castor, cotton, sorghum, pearl millet, maize and pigeon peas in *kharif* (rainy season) and linseed and chickpeas in *rabi* (winter season). The 5-year averages (1995-2000) of the irrigated area, production and the total cropped area were prepared on district basis. Crop-specific dominant rain-fed districts helped to delineate the major region for the given crop. Details on total districts in rain-fed states and 'dominant districts' covering 85 % of the rain-fed crop area are given in Table 1.

Such identification shows that each of the rain-fed crops has a particular agro-climatic niche and its cultivation is concentrated in certain selected districts. Productivity and other development activities related to a specific crop should be taken up first in these identified districts to ensure a major impact on productivity.

Table 1. Total and 'dominant districts' for the important rain-fed crops in India.

Crop	Rain-fed states	Districts covering cumulative 85 % of rain-fed area (dominant districts)
Sunflower	224	11
Soybean	202	21
Rapeseed mustard	265	29
Groundnut	316	50
Castor	202	12
Cotton	296	30
Sorghum	346	71
Pearlmillet	346	43
Maize	346	67
Pigeon pea	266	83
Chickpea	346	85

Assessment of Available Surplus Runoff for Water Harvesting and Supplemental Irrigation

The total rainfall in India is spread over few rainy days and fewer rain events (about 100 hours in the season) with high intensity resulting in large surface runoff and erosion and temporary stagnation. In either of the cases this 'green water' is not available for plant growth and has very low productivity. Local harvesting of a small part of this water and utilizing the same for supplementary/ protective irrigation to mitigate the impacts of devastating dry spells offers a good opportunity in the fragile rain-fed systems (Rockstrom 2001; Sharma et al. 2005; Wani et al. 2003). For national/ regional level planning on supplementary irrigation, one needs to make an assessment of the total and available surplus runoff and potential for its gainful utilization. In the present study, both crop season-wise and annual water balance analyses were done for each of the selected crops cultivated in the identified districts. Whereas, annual water balance analysis assessed the surplus and/or deficit during the year to estimate the water availability and losses through evaporation, the seasonal crop water balance analysis assessed changes in the temporal availability of rainfall and plant water requirements. Water requirement satisfaction index was used for assessing the sufficiency of rainfall vis-à-vis the crop water requirements.

The total surplus from a district is obtained by the multiplication of seasonal surplus with the rain-fed area under the given crop .The total surplus available from a cropped region is obtained by adding the surplus from individual dominant districts identified for each crop. An estimated amount of 11.5 M ha-m runoff is generated through 39 M ha of the prioritized rain-fed area. Out of the surplus of 11.5 M ha-m, 4.1 M ha-m is generated by about 6.5 M ha of rain-fed rice alone. Another 1.32 and 1.30 M ha-m of runoff is generated from soybeans (2.8 M ha) and chickpea (3.35 M ha), respectively. Total rain-fed coarse cereals (10.7 M ha) generate about 2.1M ha-m of runoff. Spatial distribution of runoff on agro-ecological sub- region river basin wise is shown in Figure 1. However, based on experiences from watershed management research and large-scale development efforts, practical harvesting of runoff is possible only when the harvestable amount is greater than 50 mm or greater than 10 % of the seasonal rainfall (minimum utilizable runoff, CRIDA 2001). This constitutes about 10.5 M ha of rain-fed area which generates a seasonal runoff of less than 50 mm (10.25 M ha) or less than 10 % of the seasonal rainfall (0.25 M ha). Thus, the total estimated runoff surplus for various rain-fed crops is about 11.4 million ha-m (114.02 billion cubic meters, BCM) from about 28.5 million ha which could be considered for water harvesting (Table 2). Among individual crops, rain-fed rice contributes a higher surplus (4.12 M ha-m from an area of 6.33 M ha) followed by soybeans (1.30 M ha-m from 2.8 M ha). The deficit of rainfall for meeting crop water requirement is also visible for crops like groundnut, cotton, chickpea and pigeon pea.

Long- and short-term agricultural droughts and more pronounced meteorological droughts are a common and recurrent phenomenon in the rain-fed areas served by monsoons. Though there is a good amount of surplus available as runoff in a season, all the runoff is not available at one time during the season. For the southwest Indian monsoon, usually there are two peaks of rainfall, the first occurring immediately after the onset of monsoon and the second during its withdrawal phase. During these two periods, there is a likely certainty of overflows (Ramakrishna et al. 1998) which can be harvested in suitable structures to mediate the randomness and enhance the structured supply of rainwater.

Figure 1. Spatial distribution of surplus runoff (ha-m) across dominant rain-fed districts and river basins.

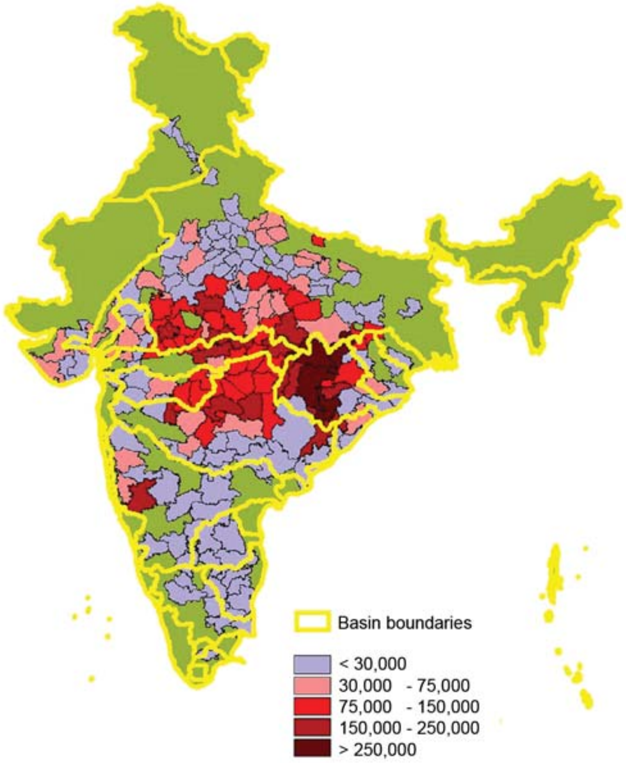

Table 2. Potentially harvestable surplus runoff available for supplemental irrigation under different rain-fed crops of India.

Crop group	Crop	Rain-fed crop area ('000 ha)	Surplus (ha-m)	Deficit (ha-m)
Cereals	Rice	6,329	4,121,851	0
Coarse cereals	Finger millet	303	153,852	0
	Maize	2,443	771,890	0
	Pearl millet	1,818	359,991	0
	Sorghum	2,938	771,660	0
Total (coarse cereals)		7,502	2,057,393	0
Fiber	Cotton	3,177	757,575	8,848
Oilseeds	Castor	28	14,489	0
	Groundnut	1,663	342,673	1,646
	Linseed	590	306,360	0
	Sesame	1,052	416,638	0
	Soybeans	2,843	1,329,251	0
	Sunflower	98	11811	0
Total (oilseeds)		6,273	2,421,222	1,646
Pulses	Chickpea	3,006	1,304,6829,166	
	Green gram	458	80135	0
	Pigeon pea	1,823	659,328	238
Total (pulses)		5,288	2,044,145	9,404
Grand total		28,568	11,402,186	19,898

Normally, farmers (depending on the method of irrigation) apply an irrigation to a depth of 30 to 50 mm as supplemental/ deficit irrigation in rain-fed areas. Actually the objective of supplemental irrigation is to adequately recharge the upper dry soil profile and connect it with the moist profile prevailing in the deeper soil layers so as to provide continuity to the flow process. In the present study, an amount of 100 mm was considered per irrigation including the conveyance and other losses. This quantity of irrigation may appear to be high but was forced due to a vast number of untrained water managers, uneven farm lands and the lack of suitable irrigation infrastructure available with rain-fed farmers.

Based on this available surplus, the irrigable area was estimated for a single supplemental irrigation of 100 mm at the reproductive stage of the crop. This was estimated for both normal rainfall and drought years. Runoff during a drought year is assumed to be 50 % of the runoff/ surplus during a normal rainfall year (based on authors' estimates for selected districts and rain-fed crops in Andhra Pradesh). The potential irrigable area (through supplementary irrigation) for both scenarios is given below (Table 3). Out of 114 billion cubic meters available as surplus, about 28 billion cubic meters (19.4 %) is needed for supplemental irrigation to irrigate an area of 25 million ha during a normal monsoon year thus leaving about 86 M ha-m (80.6 %) to meet

Table 3. Irrigable area ('000 ha) through supplemental irrigation (100 mm per irrigation) during normal and drought years under different rain-fed crops.

Crop group	Crop	Rain-fed crop area ('000 ha)	Irrigable area ('000 ha) during normal monsoon	Irrigable area ('000 ha) during drought season
Cereals	Rice	6,329	6,329	6,215
Coarse cereals	Finger millet	303	266	224
	Maize	2,443	2,251	1,684
	Pearl millet	1,818	1,370	837
	Sorghum	2,938	2,628	1,856
Total (coarse cereals)		7,502	6,515	4,601
Fiber	Cotton	3,177	2,656	1,725
Oilseeds	Castor	28	25	22
	Groundnut	1,663	1,096	710
	Sesame	1,052	919	741
	Soya beans	2,843	2,843	2,667
	Sunflower	98	59	30
Total (cilseeds)		5,684	4,942	4,171
Pulses	Chickpea	3,006	2,925	2,560
	Pigeon pea	1,823	1,710	1,374
Total (pulses)		4,829	4,634	3,934
Grand total		27,520	25,076	20,647

river/environmental flow and other requirements. During drought years also about 31 billion cubic meters is still available even after making provision for irrigating 20.6 million ha. Thus it can be seen that water harvesting and supplemental irrigation may not seriously jeopardize the available flows in rivers even during drought years or cause significant downstream effects in the normal years.

Rainwater Use Efficiency and Production Potential of Rain-fed Crops

Water use efficiency (WUE), is normally defined as grain yield (or value of the produce) per unit of water used/ transpired, measured in kilograms (or monetary units) per hectare per millimeter of water (kg/ha/mm, $/ha/mm) applied/ used (Molden 2001). At a regional scale, the estimation of rainwater use efficiency (RWUE) could be obtained by aggregating the rainwater use efficiency available at field scale. However, it is not a viable practical solution as the data requirement is quite large (in terms of productivity values from each parcel of land, inflow/outflow as surface/ sub-surface flow from cultivated fields etc.). Thus, a simple method to estimate RWUE at regional scale is to utilize the existing database of productivity statistics (available at district level) and to derive the estimate of rainfall utilized for production purposes (i.e., rain water use efficiency as a ratio of productivity at district level to the effective rainfall).Water use efficiency under rain-fed agriculture is not a consistent value as evidenced in irrigated agriculture. In rain-fed areas, the WUE varies from district to district and from year to year based on the pattern of rainfall occurrence with drought years giving a higher value of water use efficiency. The present study aggregates water use efficiency at district level for major rain-fed crops. At the field level, the effective rainfall was estimated by the procedure developed under CROPWAT and water productivity was estimated as the ratio of crop productivity at district level (5-year average) to the effective rainfall received at the district. This analysis was carried out for various rain-fed crops in respective dominant rain-fed districts. Achievable yields from on-farm trials and long-term average rainfall for each dominant rain-fed district and for different rain-fed crops were used for estimating the 'achievable' water use efficiency (Table 4).

Table 4. Estimated water use efficiency values based on 'achievable yields' (improved technologies) for different rain-fed crops*.

Crop group	Crop	Water use efficiency (kg/ha/mm)		
		Average	Maximum	Minimum
Cereals	Rice	9.40	7.34	11.29
Coarse cereals	Finger millet	6.80	6.30	8.01
	Maize	10.97	8.44	13.70
	Pearl millet	8.67	6.96	11.31
	Sorghum	13.51	11.22	17.72
Fiber	Cotton	1.60	1.23	1.97
Oilseeds	Castor	3.50	3.18	3.67
	Groundnut	3.75	2.88	4.69
	Sesame	3.11	2.48	3.68
	Soybean	7.11	5.38	8.15
	Sunflower	3.05	2.97	3.13
Pulses	Chickpea	5.19	3.90	6.25
	Pigeon pea	2.44	1.86	2.96

Note: * Based on long-term on-farm data from the national network on rain-fed agriculture.

Production projections were made for different crops in the respective rain-fed districts using the information on regional rainwater use efficiency from both scenarios, namely; district averages and on farm trials hereafter referred to as 'traditional practices' and 'improved technologies', respectively and supplemental irrigation of 100 mm at reproductive stage. Secured crop water supply (though of a limited amount) during critical drought spells reduces the risks for crop failure, thereby increasing farmers' incentives to invest in farm inputs, such as fertilizers, improved seeds, crop protection and diversification (Falkenmark et al. 2001). Trials of water harvesting and its strategic application (supplementary irrigation) in Burkina Faso, Kenya, Niger, Sudan and Tanzania have also shown increased yields of 2-3 times of those achieved in dryland farming (FAO 2002). The improved technologies involve the adoption of improved varieties, application of recommended doses of fertilizers, better management and follow-up on recommended package of practices etc. The estimated production projections for each crop and district and aggregates based on individual crop with improved practices and over two types of seasons (normal and drought) summarized for crops and groups of crops are given in Table 5. Additional production was a product of irrigable area, water use efficiency and the amount of irrigation. The irrigable area through supplemental irrigation (at 100 mm) for different crops during drought season varies between 50-98 % (98 % for rice crop to 50 % for sunflower districts) of the irrigable area during normal season.

Improved technologies, along with water, play an important part to harness the potential benefits. Under improved management practices an average of 50 % increase in total production cutting across drought and normal seasons is realizable with supplemental irrigation from rain-fed area of 27.5 M ha (Table 5). Production enhancement in drought season in case of rice crop is high due to higher water application efficiency and due to the sufficient surplus to

Table 5. Yield increases with supplemental irrigation (SI) in normal and drought seasons at two irrigation efficiencies (based on WUE of improved technologies).

Crop group	Crop	Rain-fed cropped area ('000 ha)	Traditional production ('000 tonnes)	Irrigable area ('000 ha)		Additional production ('000 tonnes)			
						Normal monsoon		Drought season	
				Normal season[1]	Drought season[1]	60 % SI efficiency	70 % SI efficiency	65 % SI efficiency	75 % SI efficiency
Cereals	Rice	6,329	7,612	6,329	6,215	3,549	4,141	3,776	4,357
Coarse cereals	Finger millet	303	271	266	224	107	124	97	112
	Maize	2,443	2,996	2,251	1,684	1,495	1,744	1,221	1,408
	Pearl millet	1,818	1,902	1,370	837	717	836	481	555
	Sorghum	2,938	3,131	2,628	1,856	2,091	2,439	1,616	1,864
	Total coarse cereals	7,502	8,300	6,515	4,601	4,409	5,144	3,414	3,939
Fiber	Cotton	3,177	430	2,656	1,725	252	294	178	206
Oilseeds	Castor	28	10	25	22	5	6	5	6
	Groundnut	1,663	1,182	1,096	710	244	284	176	203
	Sesame	1,052	365	919	741	173	202	153	176
	Soya beans	2,843	2,607	2,843	2,667	1,225	1,429	1,250	1,443
	Sunflower	98	49	59	30	11	12	6	7
	Total oilseeds	5,684	4,214	4,942	4,171	1,657	1,933	1,590	1,834
Pulses	Chickpea	3,006	2,367	2,925	2,560	910	1,061	866	1,000
	Pigeon pea	1,823	1,350	1,710	1,374	242	282	212	245
	Total pulses	4,829	3,717	4,635	3,934	1,152	1,344	1,078	1,244
Grand total		27,520	24,272	25,076	20,647	11,020	12,856	10,037	11,581

bring almost the entire rice cultivated area under supplemental irrigation. This would also indicate that large tracts of rain-fed rice cultivated area are covered under high rainfall zones with sufficient surplus for rainwater harvesting. Similar situation could be observed for soybean, which also reflects the concentration of crop growing area in high rainfall zones. In case of other crops, though water application efficiency is higher during the drought scenario, lack of surplus to cover entire area reduces the total production. Significant production improvements can be realized in rice, sorghum, maize, cotton, sesame, soybeans and chickpea.

The success of Green Revolution in irrigated areas is one solid example built upon irrigation and improved technologies. Everyone of the stakeholders from supplier to farmer to market responded with equal enthusiasm. A second Green Revolution is not in the offing for a long time for the reason that this needs to be staged in water scarcity/insufficiency zone. In the absence of stabilized yields, a production system of marketable value could not be put in place unlike in irrigated rice-wheat and other intensive production systems. The various stakeholders from start to end could not be enthused. However, the improved watersheds did to a little extent what irrigation could do to large assured areas. The mechanisms and processes for both scaling-out and scaling-up the impacts generated at the ‘bright spots’ have still eluded the development planners and implementing agencies in India (Sharma et al. 2005). Still, it has been observed that the input use like hybrid seed, fertilizers, and plant protection are on the increase with watershed activities especially associated with increase in supplemental irrigation and cropping intensity (Joy and Paranjape 2004). Concerted efforts are required through development of the local water resources to stretch the boundaries of these oases to cover the vast drylands.

Economics of Water Harvesting and Supplemental Irrigation

While it appears that supplemental irrigation offers scope for enhancing production from rain-fed crops across different agro-ecologies/districts, it is also essential that the same need to be economically viable. Numerous such structures have been constructed under varying agro-climatic conditions under state sponsored programs, by nongovernmental organizations and even with individual initiatives. The available literature also has good evidence on the technical and financial viability of the construction of such water harvesting structures for the improvement of productivity and diversification of agriculture in the rain-fed areas (Oweis 1997; Kurien 2005). The cost of provision of supplemental irrigation through construction water harvesting structures varies a great deal between states/ regions and locations between the same state (Sharda 2003; Samra 2007, personal communication; Table 6). Hence a simple analysis based on the national average cost for rainwater harvesting structures (INR 18,500 per hectare) was carried out for the provision of supplemental irrigation to rain-fed crops. The crop- wise annualized cost, considering the useful life of lined structures as 20 years, is given in Table 7. It suggests that an estimated INR 50 billion is annually required to provide supplemental irrigation to around 28 million hectares of rain-fed- cultivated land and about half of that amount is required for rice and coarse cereal production only. The benefit is evaluated based on the price of the crop and the yield difference from supplemental irrigation. With the adoption of improved practices in conjunction with supplemental irrigation, net benefits become positive for all crops except pearl millet indicating the need for development/ general adoption of high yielding varieties of pearl millet, which are responsive to irrigation and improved practices (Table 7). Pearl millet, sorghum and maize continue to be the crops with a very low harvest index. However, the data indicate that the net benefits improve by about, three-times for rice, four-times for pulses and six-times for oilseeds. Droughts appear to have very mild impact when farmers are equipped with supplemental irrigation and the net benefits remain stable even when runoff during a drought period gets reduced by 50 %.

Table 6. Cost of different water harvesting structures per hectare of the service area at different locations in India.

Location	Cost (Indian Rs.*.) of water harvesting structures (2000 price level)		
	Minimum	Maximum	Average
Bagbahrar (Chhatisgarh)	4,100	29,200	11,000
Dindori (Madhya Pradesh)	6,800	25,000	18,000
Keonjhar(Orissa)	19,400	35,000	27,000
Darisai(Jharkhand)	8,300	27,800	18,000
National average	18,500		

Note: *1 USD= Indian Rs. 42

Table 7. Crop-wise net benefits from supplemental irrigation under traditional practices and improved technologies during normal and drought conditions.

Crop/crop group	Rain-fed cropped area('000 ha)	Annual cost (Billion Rupees)	Net benefits under improved technologies(Billion Rs.)	
			With 65 % efficiency of SI during normal monsoon	With 75 % efficiency of SI during drought period
Rice	6,329	11.71	8.52	9.81
Finger millet	303	0.56	1.67	1.46
Maize	2,443	4.52	2.53	1.23
Pearl millet	1,818	3.36	-1.49	-2.10
Sorghum	2,938	5.44	0.95	-0.50
Total cereals	7,502	13.88	3.66	0.08
Cotton	3,177	5.88	8.27	4.12
Castor	28	0.05	0.17	0.16
Groundnut	1,663	3.08	5.79	3.32
Sesame	1,052	1.95	4.87	4.08
Soya beans	2,843	5.26	13.43	13.83
Sunflower	98	0.18	0.18	0.01
Total oil seeds	5,684	10.52	38.59	31.40
Chickpea	3,006	5.56	43.49	41.14
Pigeon pea	1,823	3.37	6.02	4.86
Total pulses	4,829	8.93	49.50	46.00
Grand total	27,520	50.91	94.40	81.42

Conclusion

Rain-fed agriculture is mainly and negatively influenced by the random behavior of rainfall, causing intermittent dry spells during the cropping season and especially, at critical growth stages coinciding with the terminal growth stage. District level analysis for different rain-fed crops in India showed that the difference in the district average yields for rain-fed crops among different rainfall zones was not very high, indicating that the total water availability may not be the major problem in different rainfall zones. Further, for each crop, there were few dominant districts which contributed most to the total rain-fed crop production. The most effective potential strategy to realize the potential of rain-fed agriculture in India (and elsewhere) appears to be harvesting a small part of available surplus runoff and reutilizing it for supplemental irrigation at different critical crop growth stages. The study identified about 27.5 M ha of potential rain-fed area, which accounted for most of the rain-fed production and generated sufficient runoff (114 BCM) for harvesting and reutilization. It was possible to raise the rain-fed production by 50 % over this entire area through application of one supplementary irrigation (28 BCM) and some follow up on the improved practices. Extensive area coverage rather than intensive irrigation needs to be done in regions with higher than 750 mm/ annum rainfall, since there is a larger possibility of alleviating the in-season drought spells and ensuring the second crop with limited water application. This component may be made an integral part of the ongoing and new development schemes in the identified rural districts. The proposed strategy is environmentally benign, equitable, poverty-targeted and financially attractive to realize the untapped potential of rain-fed agriculture in India.

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Groundwater Expansion in Indian Agriculture: Past Trends and Future Opportunities

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Introduction

The importance of irrigation for agricultural production growth in India hardly needs any emphasis. Irrigation, in 2000, contributed to 40 % of the crop area but 70 % of the total crop production. Improved reliability of water supply through canals or, more significantly through groundwater, has significantly contributed to the increase in agricultural productivity in India (Brown 2003). Recent studies show that the irrigation needs to play a larger role towards a goal of achieving a higher agricultural productivity and the national food security (Persaud et al. 2003; Kumar 1998; GOI 1999).

The National Commission of Integrated Water Resources Development (NCIWRD) projections show that the irrigated area should increase by about 35 million ha to reach the food self-sufficiency goals (GOI 1999). A major part of the NCIWRD additional irrigated area projection is from the surface water, and it is a key factor for the proposed national river linking project (NRLP) concept of India. The NRLP envisages transferring 178 km^3 water from the water rich Himalayan rivers to water stressed southern and western part of India and irrigating additional 34 million ha (GOI 1999).

Currently, however, India is on a cross road of its future direction of irrigated agriculture. Many opponents of the Government of India's NRLP concept argue that groundwater irrigation can contribute in providing much of the additional irrigation needs in the future. It is true that groundwater was the major driver of net irrigated area expansion in the last two decades (FAO 2002). But how long can this trend continue and in which location and in what magnitude? And how will the net groundwater area expansion contribute to gross irrigated area growth? To answer this it is necessary to review the past spatial and temporal trends of surface and groundwater irrigation and assess their contributions to the gross irrigated area growth.

The recent boom in groundwater irrigation is due to many reasons. First, due to slowing down in the growth of public investments in large-scale irrigation infrastructure and incompletion of on going projects, the surface irrigated area has not increased in the 1990s (Gulati et al.1999). The most severe problem facing Indian canal irrigation, however, is the rapid deterioration of systems that have already been created (Gulati et al. 1999). In the absence of new large-scale surface irrigation schemes, and the availability of low cost electric and diesel pumps coupled with little or no electricity charges, the groundwater has been a major driver in the irrigated area expansion. Second, expansion of groundwater-irrigated areas is in large part due to the increase in the reliability of water supply. Groundwater irrigation, due to its lesser variation in its supply and higher reliability in irrigated water supply, reduces the risk of investment in labor, seed, fertilizers, pesticides and other inputs and induces the farmers to increase the agricultural productivity.

It is popularly believed that the recent groundwater irrigation expansion was taking place in and close to irrigation command areas, where recharge from canal irrigation is the main source of groundwater availability. We hypothesize such widely held belief and examine whether canal irrigation recharge is a necessary condition for the groundwater expansion. We also test the hypothesis that groundwater boom in India is largely contributed by demand factors, for instance, rural population whose livelihood depends mostly on agriculture.

There are two main sources of growth in the gross irrigated area: expanding the irrigated area and increasing the frequency with which it is irrigated (irrigated land use intensity[1]). India's net irrigated area has expanded by 24 % and 18 % in the 1980s and 1990s. The irrigated land use intensity, representing one of the criteria of irrigated land productivity, has increased by only 10 % over the past two decades. The average national irrigation land use intensity in 2000 was 138 %. Is there any scope for increasing irrigation intensity further in existing lands? How will the surface and groundwater irrigation contribute to irrigation intensity increase? Answers to these are important to know. How much new surface is irrigated to develop for meeting future needs? Therefore, with a view to evaluating investment in major and minor irrigation projects in the light of intensive land use cropping, we here made an attempt to assess the contribution of the different sources of irrigation on gross irrigated area, which reflects the irrigated land use intensity.

The structure of the paper is as follows. In the next section, we discuss the study objective, data and methodology. The following section discusses the spatial and temporal trends associated with the groundwater boom in India. In the third section, we review the growth of the irrigated area of India in the past, and assess the contribution of different sources of irrigation on gross irrigated area. Finally, the last section summarizes the findings and results of the paper.

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[1] There are many crops like sugarcane, banana, coconut etc. that stand for more than 3 months in the field. In commuting the intensity it need some special consideration. Unlike the conventional measure of irrigation intensity, defined as the ratio of gross irrigated area (GIA) to net irrigated area (NIA), (GIA/NIA), we have computed irrigated land use intensity (ILUI) as

$$\frac{gia + \sum_{j}^{n} nia^{j}}{nia}$$

where j is the number of annual and perennial crops, which stands more than one cropping season in the field.

Study Objectives, Data and Methodology

The major objectives of this study are to assess the spatial and temporal trends of surface and groundwater irrigated area development in India and their contribution to gross irrigated area growth. Specifically this study assesses

1. whether the growth in surface irrigation is a necessary factor in net groundwater irrigated area growth;
2. whether the rural population is a driver in groundwater expansion and if so where it is most significant; and
3. the relative contribution of surface and groundwater irrigation in increasing the gross irrigated area.

Data

We use a combination of time series and cross sectional data for our analysis. The time series data from 1951 to 2001 assess the national level temporal trends of net surface, tanks and groundwater irrigated area growth; and the sources of this data are the various issues of 'Agriculture at a Glance' publications by the ministry of agriculture (GOI 2005). The district level net surface, tank and groundwater irrigated areas in 2000 assess the spatial trends, and the sources for this data are various publications of Fertilizer Statistics (FIA 2000). The relative contributions to gross irrigated area growth are assessed using time series and cross section data of 16 major states in India. These 16 states constitute more than 95 % of the agrarian economy of India, for the period 1990-1996. Instead of using aggregate time series data only, we use panel data, where the cross sectional units are the different district. This allows for district-specific variation in all the variables included, as compared with all- India data that could reduce such variation by aggregating some variables and averaging others. The source of this data is the database available in International Crops Research Institute for Semi Arid Tropics (ICRISAT).

Methodology

We use piece-wise time series regression analysis to assess the temporal variation of net surface and groundwater irrigated area growth. Spatial autocorrelation analyzes the spatial association of groundwater and surface irrigation expansion. The hypothesis here is that the percentage of groundwater irrigated area in a district is spatially associated with the percentage of the surface irrigated area of the neighboring districts.

The global Moran's I, a measure of spatial autocorrelation, shows the strength of the spatial dependence of a unit with its neighboring units (Anselin 1995). Moran's I is the degree of linear association of a variable in X-axis with its spatial lag variable in the Y-axis. The Morans's I takes values between -1 and 1. The two extremes indicate high-high or low-low spatial dependence (Morans I =1) and high-low and low-high spatial dependence (Moran's I=-1). Moran's I close to zero show no significant pattern of spatial dependence.

For our analysis we estimate the bivariate Moran's I. The bivariate Moran's scatter plot shows the spatial lag of the groundwater-irrigated area variable in the Y-axis and the surface irrigated area variable in the X-axis. The Moran's I not significantly different from zero supports our hypothesis that groundwater expansion of a unit is not necessarily associated with the surface irrigation expansion of the neighboring units.

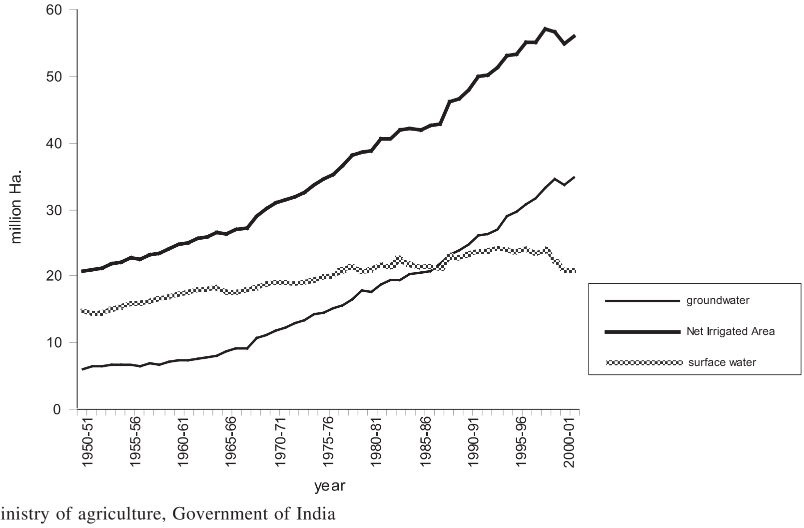
Groundwater Irrigation Boom in India

Groundwater Irrigation Growth

Groundwater irrigation has contributed in much of the increase in the net irrigated area of the country over the last few decades (Figure 1). The Figure 1 highlights the groundwater irrigation expansion relative to that of the net irrigated area; and no major difference in the slopes of the two curves is reflected in the last few decades, which supports the claim that most of the increase in the net irrigated area is caused by groundwater irrigation. In the past, surface water irrigation had played a significant role in increasing the net irrigated area. However from mid-60s, the proportion of surface water to net irrigated area has decreased and in the last decade alone it has decreased largely by 23 %. Policymakers claim that this is largely due to incompletion of planned irrigation projects and poor maintenance of the existing surface irrigation infrastructure (Gulati et al. 1999).

There seems to be three distinct periods of groundwater irrigation growth. Between 1950 and 1966, the groundwater contribution increased from 28 to 34 % of the net irrigated area. During this phase groundwater irrigation development was confined mainly to the arid and semi arid regions of the western India. In Gujarat, for instance, groundwater irrigation was the only predominant source of irrigation, and accounted for more that 80 % of the net irrigated area. Since 1967, groundwater expanded rapidly and overtook the surface irrigated area by 1982. Over the period from 1967 to 1982, groundwater added 11 million ha to the net irrigated area at a compound growth rate of 4.2 % compared with 2 % in the previous phase; while the surface irrigated area expanded only by 3 million ha. This phase can be linked to the period of green revolution agriculture, which was water intensive in nature and dependent on timely and assured supply of water. The necessity of assured water supply posed in the 1960s by the advent of green revolution technology provided the early impetus for the groundwater development in

Figure 1. Groundwater and surface irrigated area during the last 50 years.



Source: Ministry of agriculture, Government of India

Note: surface water includes both canal and tank irrigated area.

India. Evidence strongly reveals that during this period, groundwater expansion had taken place mainly in the agricultural states like Punjab, Haryana; and the correlation between groundwater irrigation expansion and surface irrigation development is strong in this phase. The last phase, between 1982 and 2001 shows the continuation of accelerated groundwater expansion at a rate of 3.14 % growth rate, and virtually no growth in surface irrigation. During this phase, groundwater irrigation growth also has taken momentum in the eastern and southern India, and mainly driven by demand factors like population pressure. By 2000, the groundwater irrigated area of 35 million ha accounted for 61 % of the total net irrigated area in India.[2]

Table 1. State-wise groundwater source of irrigation from the period 1961-1963 to1998-2000.

	NIA million hectares					Groundwater irrigated area - % of NIA				
States	1961-63	1971-73	1981-83	1991-93	1998-00	1961-63	1971-73	1981-83	1991-93	1998-00
Haryana	1,372	1,576	2,246	2,631	2,870	—	39	46	47	50
Himachal Pradesh	40	92	92	99	110	—	2	4	5	10
Punjab	3,191	2,961	3,447	3,904	4,000	31	54	59	60	70
Uttar Pradesh	5,060	7,120	9,626	10,802	12,570	47	57	61	70	73
North	9,663	11,750	15,411	17,436	19,540		53	58	62	68
Assam	617	572	572	572	570	—	—	—	—	1
Bihar	1,997	2,274	2,758	3,348	3,560	15	26	34	47	56
Orissa	1,019	1,072	1,215	1,979	2,010	3	7	17	39	40
West Bengal	1,351	1,489	1,604	1,911	2,130	—	—	14	37	52
East	4,984	5,407	6,149	7,811	8,270	7	13	22	39	49
Andhra Pradesh	3,040	3,089	3,560	4,229	4,350	13	18	22	32	43
Karnataka	907	1,221	1,439	2,205	2,510	16	26	27	34	39
Kerela	349	439	244	334	370	3	1	—	20	30
Tamil Nadu	2,478	2,706	2,513	2,559	2960	24	31	41	45	50
South	6,774	7,454	7,756	9,327	10,190	17	23	29	36	45
Gujarat	705	1,290	2,104	2,502	2,980	82	80	79	79	81
Maharashta	1,093	1,310	1,927	2,214	2,950	56	58	57	55	65
Madhya Pradesh	963	1,607	2,470	4,572	6,180	34	38	42	49	69
Rajasthan	1,807	2,191	3,101	4,255	5,360	56	54	63	61	70
West	4,568	6,399	9,602	13,543	17,470	56	56	60	59	71
India	25,479	31,975	41,048	50,500	55,910	30	40	47	52	61

Source: Ministry of agriculture, Government of India

Note: Data not available

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[2] Separate data on conjunctive usage of groundwater and surface irrigation is not available.

To get further insight, we explore the state wise net irrigated area (NIA) and the groundwater irrigation share in Table 1. The table shows the NIA and groundwater irrigated area as a percentage of NIA for the periods 1961-63, 1971-73 , 1981-83 , 1991-93 and 1998-2000. Many climatic factors like rainfall and drought affect irrigation. So, we have taken a three-year average for the periods mentioned.

National growth of groundwater irrigation masks the regional variation in groundwater irrigation expansion. There is state wise variation in the groundwater source of net irrigated area, which is reflected in Table 1. Part of this disparity in groundwater irrigation development can be explained by the fact that during the period of the Green Revolution, Punjab and Haryana were way ahead of other states in terms of irrigated area; and in the western states, particularly Gujarat and Rajasthan, groundwater was the major available source for irrigation in the post independence period. In the post 1997 period, the proportion of groundwater irrigation to net irrigated area became more than 60 % in the northern and western states, while the share of groundwater irrigation is still less than 50 % in the southern zone. Here the hydro-geo-morphological features are not as favorable as in the alluvial plains of Gangetic Basin, for recharge.

In the latter geographic zone, growth is mainly confined in Andhra Pradesh and Kerala, whereas not much growth has taken place in the Tamil Nadu and Karnataka due to declining groundwater table. The rate of expansion on groundwater irrigated area in the eastern India (West Bengal and Bihar) is phenomenally high compared to the other states during 1990s. Recent studies also show that more than one-third of total pumps in India in early 1990 was in the state of West Bengal alone (Bhattarai et al. 2003).

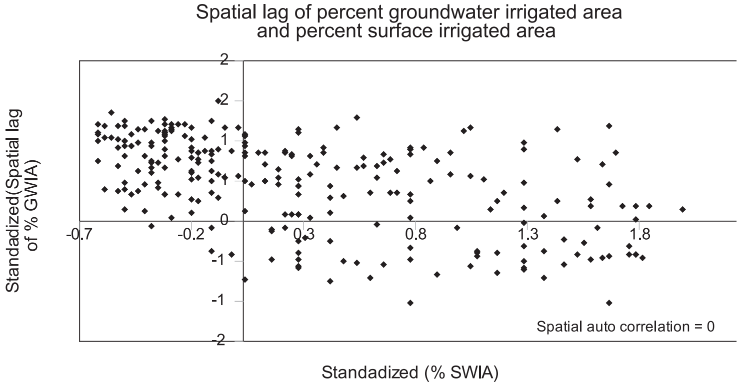
Surface Irrigation Recharge and Groundwater Area Growth: Spatial Dependence

A popular belief is that surface water recharge is a necessary condition for the expansion of groundwater-irrigated area. Groundwater pumping costs generally depend on the water table level, which means that as the groundwater stock is increased, marginal extraction costs fall. Higher surface water withdrawals recharge the aquifers and induce the farmers to increase groundwater usage and expand the gross irrigated area.

It could be true that surface irrigation recharges groundwater not only in the canal command areas, but also in the rain-fed areas outside the canal commands. But, how widespread can this recharge be, and to what extent this contributes to NGWIA expansion?

We attempt to address the issue by investigating the link between surface irrigation recharge and the groundwater irrigation expansion using spatial auto correlation analysis. Here, first we attribute the groundwater area expansion within a district to the surface irrigation in that district. (see annex A for the distribution of groundwater and surface irrigated area across districts). How would then the surface irrigation within a district be associated with the groundwater irrigation in the surrounding districts? Our null hypothesis is that the groundwater expansion in the surrounding districts is dependent on the surface irrigation of the central district. Spatial autocorrelation shows the spatial dependence of a unit with its neighbors. Figure 2 is the scatter plot of the surface irrigated area in the X- axis and the spatial lag of the groundwater irrigated area in the Y -axis. The spatial autocorrelation, which indicates the strength of the linear relationship of the two variables, is not significantly different from zero. This contradicts the hypothesis that the surface irrigation is a necessary condition for large scale expansion of groundwater expansion in surrounding areas.

Figure 2. Surface clusters of major groundwater irrigation districts.



Groundwater Area Expansion: Demand Driven Factors

As groundwater is tapped in cases where the resource is not necessarily recharged by surface irrigation, the alternative hypothesis could be that demand driven factors are behind the groundwater expansion. Evidence suggests that groundwater expansion is taking place where people are, and is not necessarily dictated by the endowment of groundwater resource.

The most important challenge of India's future agriculture is that of exploding population (Patel 2004; Thakkar 1999). India's current population is 1,100 million and is projected to increase to about 1,600 million by 2050. For major part of this population agriculture will remain as the primary source of livelihood. India's agriculture dependent population relative to the total population has been decreasing over the last few decades. However, the total agriculture population is increasing, albeit at a decreasing rate of 1.1 % in the 1980s and 1.0 % in the 1990s. Despite the increasing agriculture dependent population, the net sown area, NSA) has remained more or less constant in the last decade.[3] Thus the population pressure and the need for adequate livelihood opportunities for the increasing population on the available agriculture land have increased substantially over this period.

Boserupian hypothesis states that an increase in population density increases the intensification of agricultural factor use (Boserup 1981; Boserup 1965). We investigate whether the increase in rural population density will influence the groundwater-irrigated area of the country in the future and support the Boserupian hypothesis. The regression model shown below (equation 1) indicates positive association between groundwater irrigation expansion and rural population density. The results suggest that a percent increase in rural population density (RP) increases the proportion of groundwater-irrigated area (GW) by 5 %. The R-square of 40 % supports the claim that rural population density alone significantly accounts for the increase in groundwater irrigation expansion and supports the Boserupian hypothesis.

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[3] The NSA is about 142 million ha over this period. The NSA per person in the agriculture dependent population has decreased from 0.29 ha/person in 1990 to 0.26 ha/person in 2000.

$$GW = .03 + .05RP^* \quad (2.70)\ (6.99) \qquad (1)$$

$$R^2 = .39 \quad n = 412$$

** statistically significan at 0.001 level. Figures in parenthesis indicate the t statistics.*

Note: GW = groundwater irrigated area as a proportion to net sown area.
RP= rural-population density.

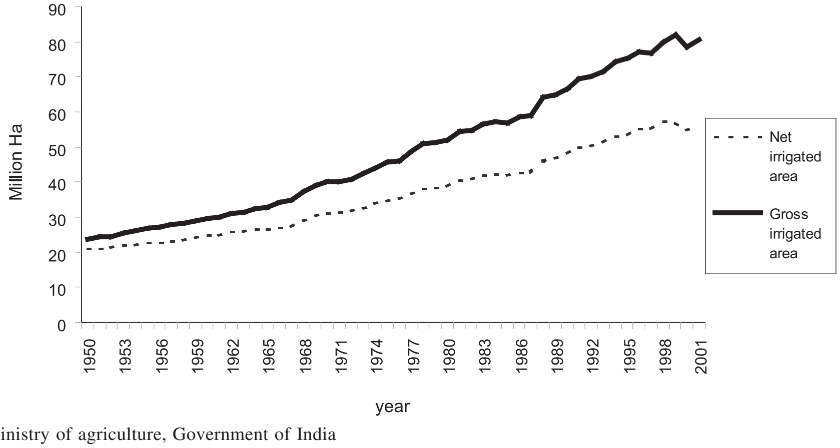
The results suggest a straightforward implication that in future, with more growing population of India, there will be more pressure to expand the groundwater-irrigated area. Higher population will exogenously increase the demand for agricultural products and in the factor market there would be increased demand of irrigation to meet the agricultural demand of the population. Groundwater irrigation being a democratic resource and an easy-to–access source of irrigation always has the opportunity to respond to such increase in demand in a much shorter time path, which is not the case for surface irrigation schemes. Thus, groundwater remains the most popular choice among the farmers to meet the market demand. If a similar trend continues, groundwater irrigation may continue to be the main source of irrigation to meet the future agricultural demand in India.

Gross Irrigated Area Growth

Groundwater Irrigated Area: Spatial Variation

During the last 50 years, gross irrigated area (GIA) of India has increased more than three fold from 24 to 81 million hectares. Gross irrigated area is a straightforward multiplicative function of net irrigated area (NIA) and irrigated land use intensity (IRLUI). Thus the relevant question, which may arise here, is the contribution of different sources of irrigation in increasing the gross irrigated area.[4] Figure 3 shows the change in net and gross irrigated area. The increasing

Figure 3. Gross and net irrigated area of India during 1950-2000.



Source: Ministry of agriculture, Government of India

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[4] We have modified the usual definition of gross irrigated area to account for annual and perennial crops.

vertical distance between the two curves signifies the contribution from the irrigated land use intensity. The figure below illustrates the increasing role of irrigation intensity, which has increased by more than 4 % in the last decade.

There are state wise variations in irrigation, as reflected in Table 2. The level of irrigation is measured in terms of irrigated land use intensification (IRLUI) and irrigation ratio, (NIA/ NSA) in percent. Table 3 shows the average of NIA, IRLUI, IR, and their corresponding growth rate. Table 3 shows a high proportion of irrigated land, more than 70 % in agricultural states like Punjab, Haryana and Uttar Pradesh where agriculture constitutes more than 30 % of the

Table 2. Irrigation scenario during the period 1990-1993 and 1998-2000.

	1990-1993		1998-2000		Growth rates (percent 1997-2000 over 1990-1993) %	
States	Irrigation land use intensity (IRLUI) %	Irrigation ratio (IR) %	Irrigation land use intensity (IRLUI) %	Irrigation ratio (IR) %	IRLUI	IR
Haryana	132	74	140	80	6.1	8.1
Punjab	138	95	139	94	0.7	-1.1
Himachal Pradesh	133	17	140	20	5.3	17.7
Uttar Pradesh	140	61	141	71	0.7	16.4
North Zone	136	67	139	75	2.2	11.9
West Bengal	138	35	141	39	2.2	11.4
Bihar-	123	46	124	48	0.8	4.4
Orissa	130	32	131	33	0.8	3.1
Assam	121	21	124	21	2.5	0
East Zone	134	36	137	38	2.2	5.6
Karnataka	134	20	140	24	4.5	20
Kerala	133	17	139	17	4.5	0
Tamil Nadu	136	43	137	54	0.7	25.6
Andhra Pradesh	138	39	140	41	1.5	5.1
South Zone	135	31	138	36	2.2	16.1
Gujarat	124	23	129	31	4	34.8
Maharashtra	135	11	140	17	3.7	54.6
MP	131	20	132	31	0.8	55
Rajasthan	136	24	137	33	0.7	37.5
West Zone	133	19	136	28	2.3	47.4
INDIA	132	35	135	39	2.3	11.4

Note: IRLUI=irrigated land use intensity
IR=Irrigation ratio defined as the net irrigated area to net sown area in percent.

Source: Ministry of agriculture, Government of India state GDP. Among the southern states, the proportion of irrigated land is below 30 % in Karnataka and Kerala; while in Andhra Pradesh and Tamil Nadu, NIA/NSA is above 40 %.

Among the western states, Maharashtra has the lowest proportion of irrigated land where only 17 % of the net cropped area is irrigated. Most of the eastern states are well endowed with irrigation where average NIA/NSA is 0.40. In the north-eastern state of Assam, however, less than 10 % of net cropped area is irrigated. In Punjab and Kerala, there is a slight decrease in the proportion of irrigated area, even with an increase in NIA.

It suggests that in post 1997 period, more rain-fed area has been brought under cultivation in both the states. In the northern zone, there is hardly any room for irrigation development as 75 % of the net cropped is irrigated, and is reflected in lower growth. The growth of irrigation area is striking in the western zone where NIA has grown by 46 % from 1990-1993 to 1997-2000. Eastern states register a much slower growth of irrigation except West Bengal. Among the southern states, higher growth in NIA took place in Andhra Pradesh and Tamil Nadu.

All states register an increase in irrigated land use intensity (IRLUI). Much of this increase is noticed in states like Haryana, Himachal Pradesh, Karnataka, Kerala and Maharashtra. In Haryana, the increase in intensive use of irrigated land is contributed by limitation to increase the net irrigated area. In the latter three states, higher intensive use of land is also contributed by the choice of cropping pattern. In these four states, the share of permanent crops is high compared with that of other states.

In these states, however, the proportional irrigated area is not high. One possible reason could be that the opportunity cost of increasing the net irrigated area is higher than increasing the intensity. As a result, irrigated land use intensity became the major driver of gross irrigated area in these states with the development of minor irrigation.

Gross Irrigated Area Expansion: Sources of Growth

Different sources of irrigation contribute in increasing the gross irrigated area (GIA). These sources include canal irrigation, tank irrigation and groundwater irrigation with tube wells and dug wells. We assess the patterns of GIA growth in four groups. The first group consists of districts with canal, groundwater and tank irrigation. In these districts surface irrigation has indeed contributed to increasing groundwater recharge. The second group consists of districts with only canal-irrigated area. The third group consists of only groundwater irrigation districts. Before the introduction of groundwater, these districts were mainly rain-fed districts. The groundwater recharge in these districts is mainly from rainfall. The fourth group of districts consists of only tank and groundwater irrigated area. These districts are located mainly in the southern peninsular states.

We use a simple ordinary least squares regression to assess the contribution of surface, tanks and groundwater area expansions to GIA. The regression in the first group of districts, where canal, tanks as well as groundwater irrigation are present, a percentage increase in groundwater irrigation will increase the GIA by 1.47 times. In the first group, a percentage increase in canal irrigation will increase the GIA by 1.42 times. In districts without canal irrigation, the marginal contribution on GIA drops to 1.37. However, the marginal effect of groundwater contribution on gross irrigated area is only 1.22 in districts irrigated using groundwater only. The areas were primarily the rain-fed areas where groundwater expansion has taken place. The marginal contribution of canal irrigation in the command area, where only canal-irrigated area is present, is 1.98. It implies that a percentage increase in canal-irrigated area in the command area will increase the gross irrigated area by 1.98 %. The regression results (Table 3) lead to the following two key issues.

- Why is that the marginal effect of groundwater irrigation on gross irrigated area is not high in the districts without canal irrigation (third group)?
- If there is not much significant difference with rain-fed intensity why then the farmers irrigate with groundwater in such cases?

Table 3. Regression results explaining the impact on gross irrigated area.

Types of irrigation		Regression equation
Canals, tanks, and well irrigated lands	1	$GIA = -32.30 + 1.42\,Canal + 1.01\,Tank + 1.47\,Totwell$ $R^2 = .81$ (-6.83) (55.18) (8.43) (49.98) n = 1476
Only canal irrigated lands	2	$GIA = -8.53 + 1.98\,Canal$ $R^2 = .30$ (4.05) (3.52) n = 312
Only well irrigated lands	3	$GIA = 16.92 + 1.22\,Totwell$ $R^2 = .62$ (3.56) (20.68) n = 932
Well and tank irrigated lands	4	$GIA = 6.88 + 1.29\,Tank + 1.36\,Totwell$ $R^2 = .76$ (3.15) (36.61) (49.78) n = 1164

Notes: Figures in parenthesis indicate the t statistics.
GIA = gross irrigated area
Canal = canal net irrigated area
Tank = Tank net irrigated area
Totwel l=Total well (tube and dug well) net irrigated area

In the areas without canal irrigation, groundwater irrigation has expanded over the rain-fed area and is based on natural recharge, which is affected by the vagaries of rainfall. Moreover, as groundwater irrigation is the only form of irrigation, farmers overexploit the groundwater resource. Low groundwater recharge coupled with higher rate of withdrawal could be the reason for low irrigated land use intensity in the district where groundwater is the only form of irrigation. Despite limited scope of increasing the gross irrigated area, farmers still exploit groundwater in such areas to supplement the current water availability for higher yield. Higher agricultural productivity and population pressure are the factors behind groundwater expansion in such cases.

Based on the current level of growth in gross irrigated area, and the regression trend given in Table 3 and equation 1, we analyse the sources of changes in the gross irrigated area, which has increased by 4.7 % during the last decade. The computation of the source of gross irrigated area growth is based on the regression analysis (Annex B for details). Table 4 shows the contribution of different sources to the relative change in average irrigation intensity.

Groundwater irrigation contributed around 90 % of the relative change in gross irrigated area in India during the period 1990-1993 and 1998-2000, while canal irrigation contributed less than 10 % of the change. Higher relative contribution of groundwater is also witnessed in all geographical zones. However, only in the east zone, relative contribution of canal irrigation is around 30 %, which is higher than that of other regions.

Table 4. Sources of gross irrigated area growth in the last decade.

	Sources of GIA growth (%)				
	INDIA	North Zone	East Zone	South Zone	West Zone
Canal	9.55	13.99	30.24	5.96	19.05
Tank	1.89	0.53	1.26	5.96	2.25
Groundwater	88.56	85.48	68.49	88.08	78.70
Total	100.00	100.00	100.00	100.00	100.00

Both canal and tank irrigation is subject to external factors of varying rainfall and coupled with decline in the performance of canal and tank irrigation it has contributed in the decline of gross irrigated area in the last decade. These factors have compelled many farmers to shift to well irrigation, while groundwater irrigation has taken over much of the rain-fed areas.

Conclusion and Policy Implication

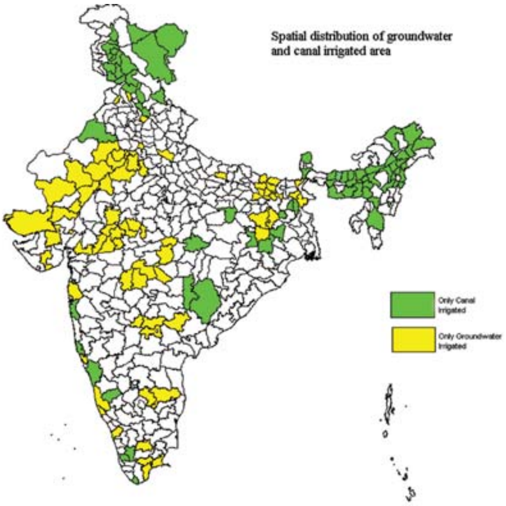
Two important findings have come out of the paper. First, groundwater irrigation expansion is driven mainly by the demand conditions-the population pressure, and not necessarily dependent on the recharge from surface irrigation. Second, the gross irrigated area, which reflects the irrigated land use intensification, is largely explained by the supply conditions, for instance groundwater recharge; and it is evident as in the districts without canal irrigation, the marginal effect of groundwater irrigation on gross irrigated is lower than that in the district with both canal and groundwater irrigation facilities.

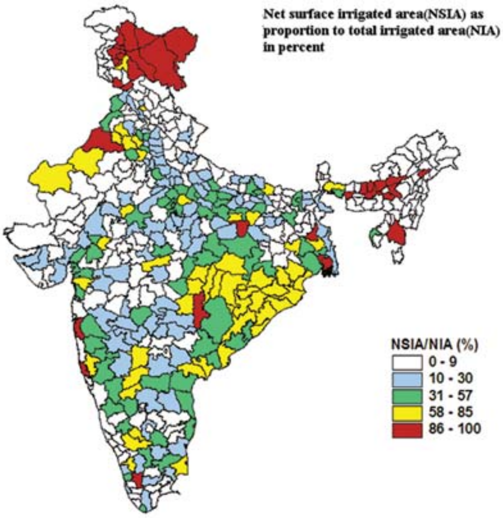
It becomes apparent from the analysis that much of the groundwater irrigation expansion is taking place where there are no facilities of canal irrigation. With the availability of low cost electric and diesel pumps coupled with little or no electricity charges, the groundwater has been a major driver in the irrigated area expansion over the rain-fed areas. However, groundwater recharge in these areas is heavily dependent on natural recharge from rainfall, which is again subject to uncertainty. Under such conditions over exploitation of groundwater may lead to well failures, which is already evident in southern and western India. In western India, half of the wells once in use are now out of commission (Deb Roy and Shah 2003). This figure will increase as water tables decline. This is also the possible reason for the low land use intensity in areas irrigated only with groundwater.

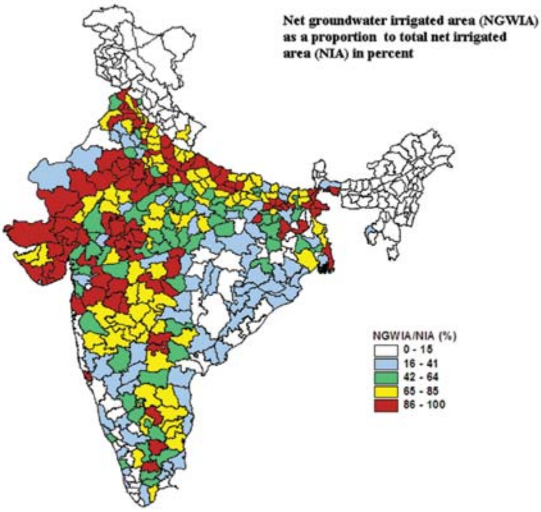
Our results also suggest that groundwater irrigation when practiced in areas endowed with canal irrigation facilities, the irrigated land use intensity is high. One of the important uses of surface water irrigation is the recharge of groundwater. Given a sustainable stock of groundwater aided by recharge from canal irrigation, groundwater irrigation is the most reliable driver to increase the intensive use of irrigated land, one of the criteria of agricultural productivity. In a situation where groundwater irrigation is the dominant form of irrigation, any surface water irrigation project in future would thus facilitate better groundwater utilization and help in increasing the land use intensification.

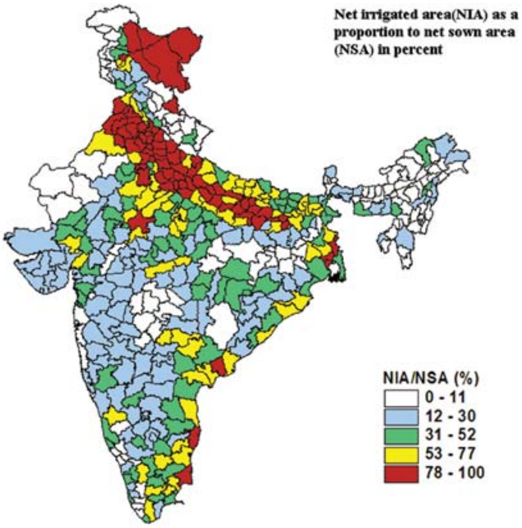
Annex A

Maps showing the districts in India irrigated with groundwater and surface water in the year 2000.






Net groundwater irrigated area (NGWIA) as a proportion to total net irrigated area (NIA) in percent
NGWIA/NIA (%)
0 - 15
16 - 41
42 - 64
65 - 85
86 - 100


Net irrigated area(NIA) as a proportion to net sown area (NSA) in percent
NIA/NSA (%)
0 - 11
12 - 30
31 - 52
53 - 77
78 - 100

Annex B

Computation of the source of gross irrigated area growth.

Suppose gross irrigated area (GIA) is a function of canals ($canal$), tanks (Tank) and groundwater ($Totwell$).

It can be expressed as $GIA = f\ (canals, Tanks, Totwell)$. Taking total change of the function, we get

$$\Delta GIA = \frac{\partial f}{\partial canal}\,[\Delta canal] + \frac{\partial f}{\partial Tank}\,[\Delta Tank] + \frac{\partial f}{\partial Totwell}\,[\Delta Totwell]$$

where $\frac{\partial f}{\partial i}$ is the marginal change of GIA due to change in i^{th} source of irrigation (i=canal, tank, Totwell), and $\Delta(i)$ is the total change in ith factor.

So the contribution of canals in the relative change of GIA from year 1990 to 2000 can be expressed as $\frac{\frac{\partial f}{\partial canal}\,[\Delta canal]}{\Delta GIA}$ or $\frac{\frac{\partial f}{\partial canal}\,\left[[canal_{2000} - canal_{1990}\right]}{[GIA_{2000} - GIA_{1990}]}$; where from Table 3 and equation 1, we get $\frac{\partial f}{\partial canal} = 1.42$

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

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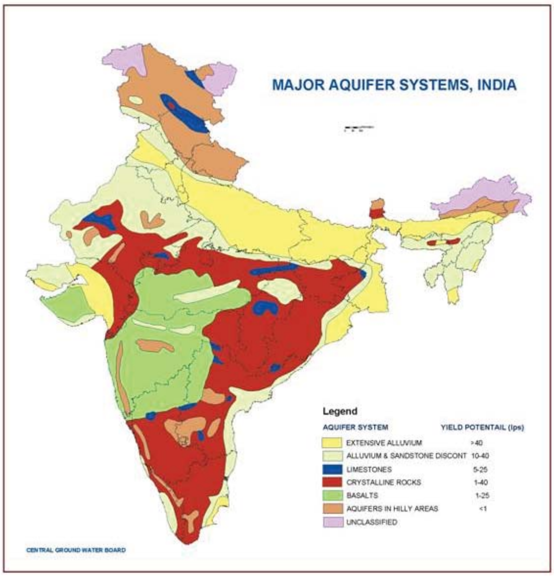
Indian Hydrogeology

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

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

Figure 1. Aquifer systems of India.



Precambrian Crystalline Province

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

Precambrian Sedimentary Province

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

Gondwana Sedimentary Province

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

Deccan Trap Province

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

Cenezoic Sedimentary Province

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

Cenezoic Fault Basins

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

Ganges-Brahmaputra-Indus Alluvial Province

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

Himalayan Highland Province

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

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

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

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

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

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

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

Note: 0 = relatively negligible area

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

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

National Picture of the Current Level of Groundwater Exploitation

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

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

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

Lacunae in Estimation Procedure

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

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

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

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

Observations from CGWB 2004 Data

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

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

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

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

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

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

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

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

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

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

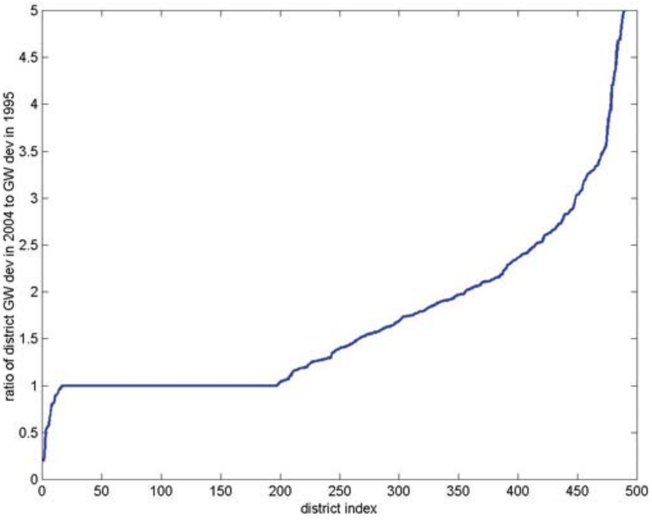
Next, the Indus Basin alluvial sand and extensive alluvial region shows a high level of groundwater development of 92 % and 86 % respectively. This includes the heavily canal and groundwater irrigated areas of Punjab and Haryana which are the areas of intensive agriculture. Many of these areas have witnessed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

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

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

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

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



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

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

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

Environmental Impacts of Overexploitation

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

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

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

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

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

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

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

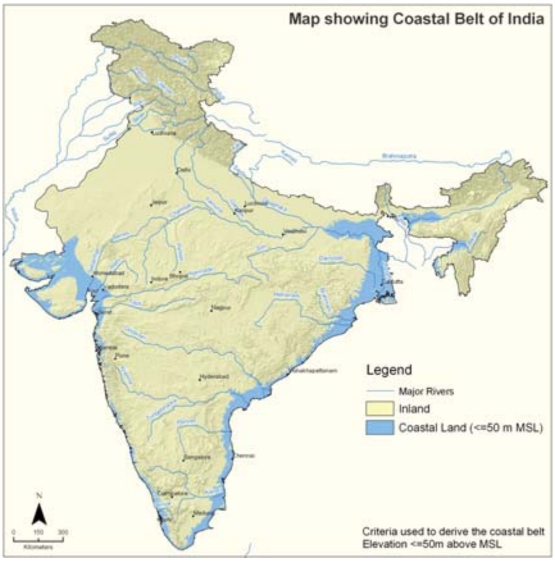
Crystalline aquifers of Tamil Nadu show a high degree of groundwater exploitation since the past 2-3 decades. The Noyyal River basin, a sub-basin of Cauvery, is a representative example of typical problems facing other areas of the state (Mayilsami et al. 2007). Increasing fluctuation of water levels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

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

Impacts on Groundwater Quality Due to Overexploitation

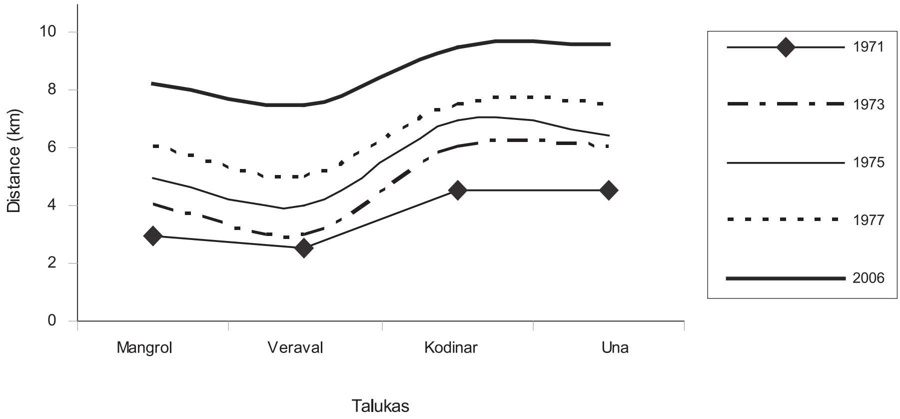
Another level of constraint on further expansion of groundwater based irrigation is the quality of groundwater. Both inland and coastal salinity together impose restrictions on the expansion of irrigation in some areas. Pockets of coastal areas are experiencing seasonal and long term trends of inland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

Figure 3. Coastal zone across India.



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

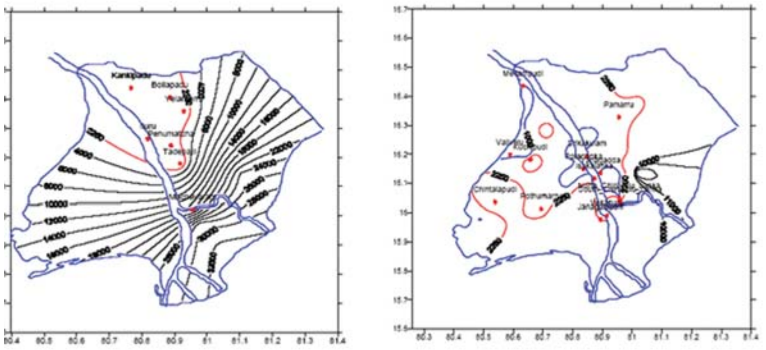
Figure 4. Salinity ingress profile in Junagadh, Gujarat from 1971 till 2004.



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

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

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



Post monsoon 1976

Post monsoon 2002

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

Impacts on Growth in Groundwater Based Irrigation

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

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

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

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

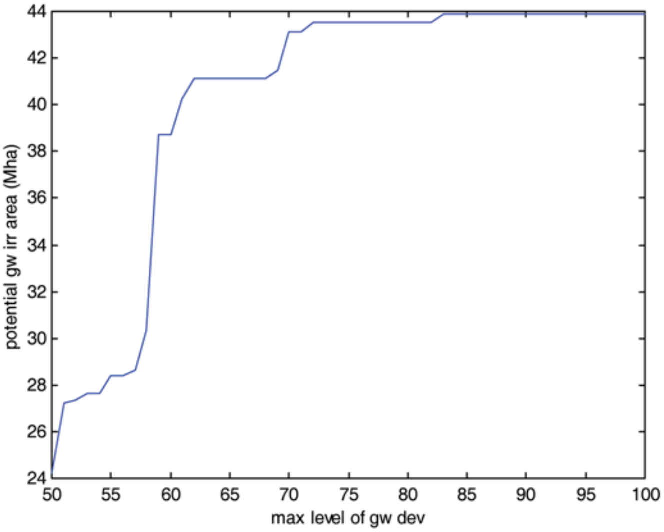
	Allu_ Sand	Aquifer_ Hills	Basalts	Cryst_ Rocks	Ext_ Alluvium	Limes tone	Un classified	All basins
‘Brahm_Bait’	0	0	0	0.1114	0	0	0	0.1344
‘Brahmaputra’	0.0857	0.2161	0	0	0.1397	0	0.3622	0.8072
‘Cauverg’	0	0	0	0.2996	0	0	0	0.3462
‘ERF_Bet_Go_Kr’	0	0	0	0	0	0	0	0.0219
‘ERF_Bet_Kr_Pe’	0	0	0	0.0502	0	0	0	0.1002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

Source: Agricultural statistics 2001

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

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

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



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

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

Urban Growth and Groundwater Exploitation

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

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

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

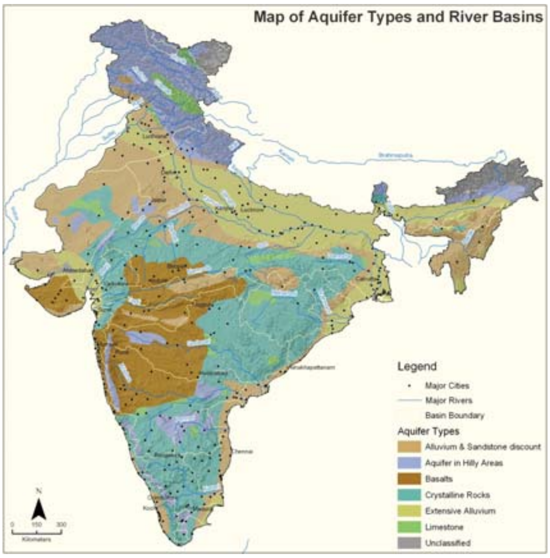


Table 5. Groundwater dependence of urban areas for each aquifer type.

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

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

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

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

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

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

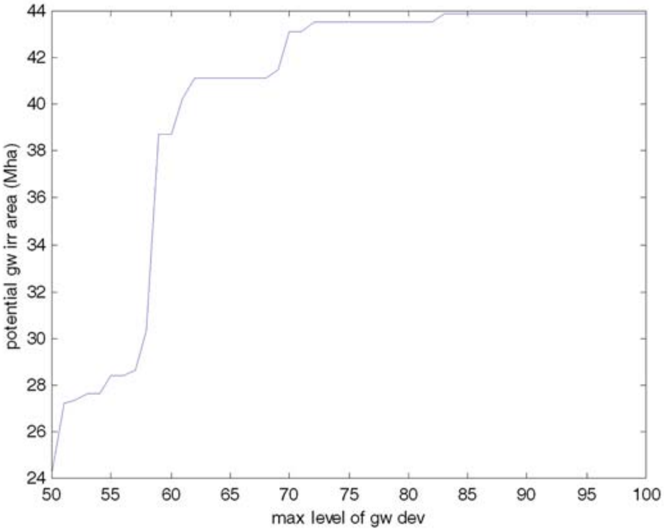
Basin	No. of towns	Average level of GW dev	Average % of GW supply in cities
Barak	5		11.34
Brahmani_Baitarn	3	34.6	66.67
Brahmaputra	5	25.9	21.82
Cauvery	17	68.2	7.35
ERF1	7	44	22.02
ERF2	18	61	22.20
Ganga	109	61.2	66.94
Godawari	18	40.6	5.37
Indus	21	68.27	66.46
Krishna	26	54.9	14.39
Luni	16	80.33	35.83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

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

Conceptualizing All Constraints on Groundwater Based Irrigation

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

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



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

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Water Productivity at Different Scales under Canal, Tank and Well Irrigation Systems

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Introduction

Generally speaking, the term 'water productivity' refers to the magnitude of output or benefit resulting from the input quantum of water as applied on a unit base. In the domain of agriculture, it is expressed as the net consumptive use efficiency in terms of yield per unit depth of water consumed per unit area of cultivation. If the field water conveyance, application, storage and distribution efficiencies are accounted to depict the seepage, runoff and deep percolation losses (not consumed by plant; evapotranspiration loss is included as an implicit component of field water balance) it would be termed as the gross irrigation water use efficiency. When isolated as 'water productivity' it becomes a partial productivity of one factor viz., water, irrespective of the land unit but in reference to the scale of production in the range of a single plant's effective root zone to a basin or system of irrigation command. As more and more water losses are incurred when the scale of reference expands, the apparent or relative water productivity is bound to decrease. However, for an increasing scale, the chances of recovering the so called 'losses' of water are bound to increase and at one stage, may be a project or basin scale, the loss at one point will be a gain at another point (as deep percolation leading to groundwater recharge or runoff leading to surface detention and storage) for recycling. In other words, the basic net input of water required in the effective root zone of a plant scale is subsequently reckoned as a gross input of water incorporating the irrigation efficiencies (h) at farm/field level and fixing the flow duty (D), field duty (D) and storage duty (S) at a system/project/basin/command level. The overall conceptual framework should account for all these transformation parameters from scale to scale.

Agricultural Water Productivity

Agricultural water productivity can be expressed either as a physical productivity in terms of the yield over unit quantity of water consumed (tonnes per ha.cm of water or kg yield per kg water consumed) in accordance with the scale of reference that includes or excludes the losses of water or an economic productivity replacing the yield term by the gross or net present value of the crop yield for the same water consumption (rupees per unit volume of water).

Water productivity is defined as 'crop production' per unit 'amount of water used' (Molden 1997). Concept of water productivity in agricultural production systems is focused on 'producing more food with the same water resources' or 'producing the same amount of food with less water resources'. Initially, irrigation efficiency or water use efficiency was used to describe the performance of irrigation systems. In agronomic terms, '*water use efficiency*' is defined as the amount of organic matter produced by a plant divided by the amount of water used by the plant in producing it (De Wit 1958). However, the used terminology '*water use efficiency*' does not follow the classical concept of '*efficiency*', which uses the same units for input and output. Therefore, International Water Management Institute (IWMI) has proposed a change of the nomenclature from '*water use efficiency*' to '*water productivity*'. Water productivity can be further defined in several ways according to the purpose, scale and domain of analysis (Molden et al. 2001; Bastiaanssen et al. 2003).

Stakeholder	**Definition**	**Scale**	**Target**
Farmer	Yield / irrigation	Field	Maximize yield
Irrigation engineer	Yield / canal water supply	Irrigation scheme	Maximize water allocation
Policymaker	$ / available water	River basin	Maximize profits

Scales of Reference and Water Productivity Transformations

The definition of water productivity is scale-dependent. Increasing water productivity is then the function of several components at different levels viz., the plant, field, irrigation system and river-basin. An increase in production per unit of water diverted at one scale does not necessarily lead to an increase in productivity of water diverted at a larger scale. The classical irrigation efficiency decreases as the scale of the system increases (Seckler et al. 2003). In India, the on-farm irrigation efficiency of most canal irrigation systems ranges from 30 to 40 % (Navalawala 1999; Singh 2000) whereas, the irrigation efficiency at basin level is as high as 70 to 80 % (Chaudhary 1997). Basin water productivity takes into consideration beneficial depletion for multiple uses of water, including not only crop production but also uses by the nonagricultural sector, including the environment. Here, the problem lies in allocating the water among its multiple uses and users.

Methodology to Workout Water Productivity

The assessment of water productivity would involve a sequence of mathematical operations that may be in accordance with the scale of reference. The scale based models are to be integrated for the final quantification of agricultural water productivity on an ultimate regional scale for the purpose of planning.

Plant/Crop Scale Water Productivity (WP [p]):

Here, the effective root zone of the plant/crop is the reference or datum over which the crop consumptive use exclusive of the inevitable gravitational irrigation system losses (seepage, runoff and deep percolation) is considered as the input for the single plant/crop output. In case of using micro-irrigation systems (drip or sprinkler) these losses are reduced to zero and the root zone gets exact replenishment through irrigation to meet the soil moisture deficit. The physiological processes such as photosynthesis, nutrient uptake and water stresses also contribute over to productivity. Hence,

total consumptive use (CU) in cm = (number of irrigations)* (depth of irrigation in cm).

Then, water productivity on a plant/crop scale WP (p) = Y/CU and the water use efficiency becomes WUE (p) = WP (p)/A, where 'A' is the effective area commanded by the plant. In accordance with the crop-crop spacing (Sc) and the row-row spacing (Sr), A = Sc*Sr. The unit of WP(p) can be kg yield per kg of water consumed or cm of water consumed and that of WUE(p) can be kg yield per cm of water consumed per square meter crop area.

Field/Farm Scale Water Productivity (WP [f]):

At a field scale, processes of interest are different: nutrient application, water conserving tillage practices, field bunding, puddling of paddy fields etc. Water enters the field domain by direct rainfall, subsurface flows and irrigation from a source of storage. Rainfall alone is considered in case of rain-fed agriculture. A field or farm scale water productivity (WP [f]) is influenced by the inevitable irrigation conveyance, application, storage and distribution losses/efficiencies. Hence, the total water diverted from storage accounting for these losses is taken as the consumptive usage. Technically,

WP (f) = WP (p)/ (η), where (η) is the overall irrigation efficiency of the farm with gravitational irrigation system layout. In case of a micro-irrigation layout, the value of (η) will be more than 95 % and almost 100 % if the design is perfect.

Since the scale of reference expands, the unit may be chosen as tonnes per cm of water consumed (t/cm).

Conveyance Efficiency $\acute{\eta}_c$ = Wdf/Wds X 100

Application Efficiency $\acute{\eta}_a$ = Wsr/Wdf X 100

Storage Efficiency $\acute{\eta}_s$ = Wsr/Wnr X 100

Distribution Efficiency $\acute{\eta}_d$ = (1-Y / d) X 100

Water Use Efficiency WUE = (Y/A)/Wdf

Where,

Wds = Volume of water diverted from the irrigation source, in m^3 or ha.cm; the source may be a well, canal distributory outlet, tank sluice outlet etc.

Wdf = Volume of water delivered on to the field, in m^3 or ha. cm

Wro = Volume of run off, m^3 or ha. cm

Wdp = Volume of deep percolation m^3 or ha. cm

Wsr = Wdf – (Wro + Wdp) = Volume of water stored in the effective root zone m^3 or ha. cm

Wnr = Volume of water needed in the root zone, m^3 or ha. cm = AX d

d = design depth of irrigation, cm

The overall field irrigation efficiency $\acute{\eta}e = \acute{\eta}_c$ X $\acute{\eta}_a$

Project/Command Area Scale

In Tamil Nadu, three distinct kinds of command areas are in vogue viz., canal (or reservoir) command, tank (system and nonsystem) command and well (groundwater) command. While the canal and tank commands mostly fall intact under a project operation, well commands occur in a scattered fashion (Figure 1). When water is distributed in an irrigation system at a major scale like this, the important processes include allocation, distribution, conflict resolution and drainage. Allocation and distribution of irrigation water are primarily for irrigation besides meeting the nonagricultural demands like domestic, industrial, livestock and fisheries.

For canal command areas, irrigation scheduling cannot be done on a micro-scale calculating the depth of irrigation required, frequency of irrigation and the duration of irrigation owing to a larger areal extent with different crops and a different system of irrigation supply throughout the season on a rotational basis. Here, irrigation scheduling refers to the quantum of water to be stored or diverted for meeting the overall command area crop and allied demands. The water productivity concept shall be redefined by way of incorporating the overall irrigation efficiency and the duty of water at storage, flow and field level. The base period (B) over which irrigation flow is continuous through the canal network with suitable time rotations at outlets for distribution, also decides the productivity.

Canal Command / Project Water Productivity (WP(c))

The overall productivity of this scale of reference depends ultimately on the total quantum of water released from storage over the base period, the area covered and the project yield. The storage duty (S) includes the losses during conveyance, distribution and application over and above the field duty (Δ) in a canal network project.

Field duty (Δ) is expressed as the seasonal water requirement for crop and related activities, in cm, at the tail most end area of the canal network.

$\Delta = CU/\eta$ where, η represents the farm/field efficiency

Then, the storage duty (S) = $\Delta / \eta(c)$ where $\eta(c)$ represents the overall conveyance efficiency of the canal network/project.

The flow duty (D) in ha/cumec is devised in accordance with S and Δ to cover the given command area (A) over the base period (B) of the project water supply, as,

$D = (864B) / \Delta$, and $S = A.\ \Delta / \eta(c)$

As the command area/project scale is expanding, the apparent losses like runoff and/or deep percolation would be considered for recycling or conjunctive use with canal flows. Then, the water productivity will be based on the total volume of water diverted from the irrigation source or simply the storage duty (S).

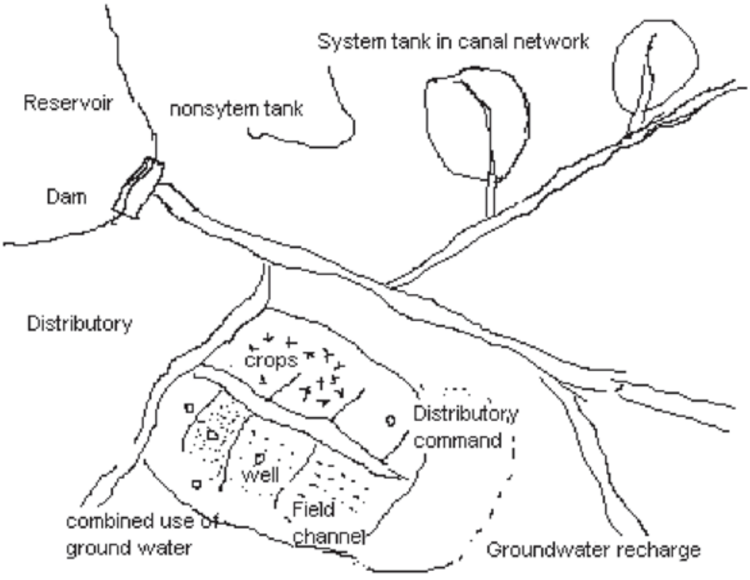
$WP(c) = Y / S$ Where,

Y = project yield, in tonnes and S = Storage duty, in ha.cm

If S is expressed in cm as S’ then, S’ = S/A

So that WP(c) = Y / S’

Figure 1. Water productivity at project/ command area scale.



Tank Command Water Productivity WP (t):

Nearly 39,000 tanks exist in the Tamil Nadu State as natural surface water harvesting structures since the olden kings’ regimes for the purpose of irrigation and other water use. Earlier the tank system had clearly defined channel network originating from the storage outlet point and in due course of time these channels have disappeared owing to encroachments and other formidable reasons. The tanks commonly come under a *nonsystem* (isolated or interconnected battery) with independent or combined catchments or a *system tank* arcade hooked along rivers or streams or canals, in which water at select points is diverted into the tank. The gross volume of water depleted from the tank storage (Sd) or the equivalent depth (Sd’) in cm, over the crop growth season forms the base (denominator) for productivity calculations.

WP (t) = Y/Sd

where,

Y = the overall tank command yield in tonnes

Sd = depleted volume of water from tank storage, ha.cm or Million cubic meters

Sd’ = equivalent depth in cm of water depleted from tank storage

Well Command Water Productivity WP (w)

Unlike the canal or tank commands, well commands are isolated and scattered and may also occur within a canal command or tank command. Absolute water productivity from an area fed by wells alone can be worked out if that area is away from a canal or tank command. But if the wells function within a canal or tank command, the conjunctive water productivity will be assessed on the premise that losses from canal or tank flows, contribute to groundwater recharge over a certain lag period, i.e., loss is transformed into a gain. Recycling this gain of water as a conjunctive use of groundwater with surface waters will help increase the irrigation area thereby increasing the absolute productivity of the region. Water table fluctuations are periodically assessed to determine if the area comes under a dark zone or gray zone or a white zone for having exploited the groundwater potential and leading to a critical stage of minimum or controlled pumping with possibilities for introducing artificial recharge means and structures. Water table fluctuations, pumping hours, discharge variations, power of pumping unit, mode of conveyance and application, type of crop and method of irrigation would contribute to the fluctuations in productivity. The productivity can be improved if lined channels or pipelines are used for conveyance and micro-irrigation systems are used for application.

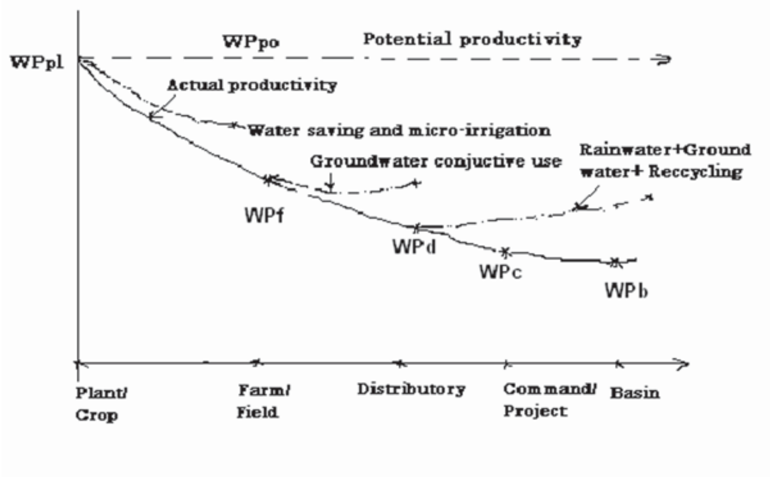
$$WP(w) = Y/Wd$$

Where,

Wd = volume or equivalent depth in cm of water depleted from well storage by pumping = (pump discharge * total duration of pumping over the crop growth season) / area of cultivation

All the above scales of reference shall be suitably formatted for input data, processing models and output units of productivity. The overall physical or economic productivity of a region shall then be worked out integrating the above scales.

Figure 2. Implications for integrated system water productivity.



Implications for Integrated System Water Productivity

- The physical water productivity (WP_p) tends to decrease at a drastic rate towards the scale expansion to farm/field level from the ideal plant/crop level with the potential productivity (Figure 2). The reason attributed is runoff and deep percolation losses, resulting in reduced efficiency levels and an increased water demand at the field inlet for diversion from the irrigation source.
- From farm/field scale the rate of reduction in productivity decreases towards a distributory scale and thereupon it may attain constancy due to the effects of the groundwater conjunctive use and recycling from the water harvesting structure for supplemental irrigation. Productivity can be improved upon by these effects.

Water Productivity Vs Scale of References under Different Irrigation Systems

Water productivity under different scale levels viz., plant, field and distributory level was studied in three different irrigation systems viz., canal, tank and well irrigation. In canal irrigation system, four river basin areas of Tamil Nadu viz., Parambikulam Aliyar Project (PAP), Lower Bhavani Project (LBP), Periyar Vaigai and Tampiraparani river basins were taken to work out the water productivity at different scales of references. Data were collected using field visits to the canal commands and also necessary information was collected from the project records. Wherever possible measurements were taken and verified. The details of water productivity under different scale levels in various irrigation systems are presented in Table 1. In canal irrigation system, groundnut is a predominant crop in Parambikulam Aliyar Project (PAP), whereas in the other three river basins rice is the major crop.

From the results, it is clearly understood that there was a considerable reduction in water productivity under field level (0.20 kg groundnut/ m^3 of water in PAP, 0.40 kg rice / m^3 in Lower Bhavani Project (LBP), 0.24 kg rice / m^3 in Vaigai and 0.27 kg rice / m^3 in Tampiraparani River basin) as compared with individual plant/ crop level (0.39 kg groundnut/ m^3 of water in PAP, 0.73 kg rice / m^3 in LBP, 0.70 kg rice / m^3 in Vaigai and 0.60 kg rice / m^3 in Tampiraparani River basin) mainly due to losses through seepage, deep percolation and runoff in the canal irrigation systems. Among the four canal irrigation projects, Lower Bhavani Project was recorded to have higher productivity at the plant level (0.73 kg/m^3) as well as at the farm level (0.40 kg/m^3) compared to other projects. At distributory level, conveyance losses caused reduction in water productivity, which means that a more quantity of water is being used for crop cultivation. So water productivity has a negative relationship with the scale of reference that is the expansion of the boundary of the command area (Figure 3).

In the case of tank irrigation, Srivilliputhur Big Tank in Ramanathapuram District of Tamil Nadu was taken for the study as the data on most of the parameters of water productivity calculations were available. The results showed that there was a reduction in water productivity when the scale of reference is increased. The physical water productivity of rice was higher under individual plant level (0.47 kg / m^3) followed by field level water productivity (0.30 kg / m^3) and comparatively lower water productivity was recorded under tank system level.

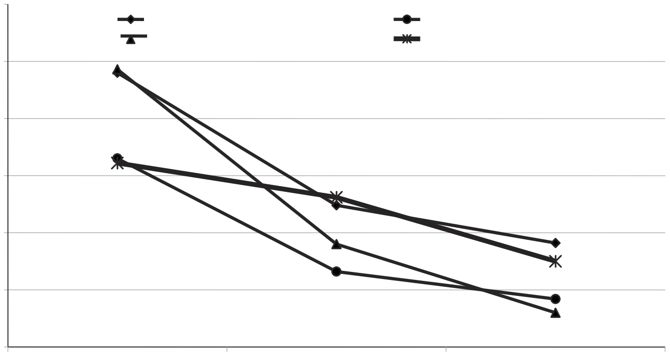
In sum, among the different irrigation systems, the well system has comparatively higher water productivity both in physical and economic terms due to controlled irrigation application, comparatively higher crop yields and multiple crops/ enterprises combinations. In canal and tank systems, mono-cropping, uncontrolled irrigations, and scarcity of water during critical crop periods result in lower water productivity.

Table 1. Physical and economic water productivity under different irrigation systems with the different scale of reference in Tamil Nadu.

Scale of references	Total water used (m^3)	Output		Water productivity	
		Physical (Rs.)	Economic (kg/m^3)	Physical ($Rs./m^3$)	Economic (kg)
I. Canal system					
1. Parambikulam Aliyar Project (PAP)					
Plant/ crop level	0.013	0.0051	0.0312	0.39	2.40
Field level (0.4 ha)	3,388.8	680	4,160	0.20	1.23
Distributory level	1,335,283.7	1,85,661	1,135,810	0.14	0.85
2. Lower Bhavani Project (LBP)					
Plant/ crop level	0.0180	0.0131	0.029	0.73	1.61
Field level (0.4 ha)	5,473.5	2,200	7,000	0.40	1.28
Distributory level	8,33,824.4	2,13,796	6,21,952	0.26	0.75
3. Vaigai River Basin					
Plant/ crop level	0.020	0.014	0.033	0.70	1.65
Field level (0.4 ha)	6,931.25	1,650	4,390	0.24	0.63
Distributory level	2,486,534.4	3,96,000	1,053,600	0.16	0.42
4. Tampiraparani River Basin					
Plant/ crop level	0.028	0.017	0.068	0.60	2.43
Field level (0.4 ha)	7,909.4	2,100	7,100	0.27	0.90
Distributory level	37,647,968.0	3,549,038	12,066,949.5	0.09	0.30
II. Tank system					
Plant/ crop level	0.0202	0.0095	0.007125	0.49	0.35
Field level (0.4 ha)	11,608.1	3,160	2,375	0.27	0.20
System level	3,099,174	8,21,000	9,54,750	0.26	0.30
III. Well system					
Plant/ crop level					
Maize	0.048	0.050	0.21	1.04	4.38
Banana	6.6	8.5	59.70	1.28	8.99
Field level					
Crops alone (0.9 ha)	12,003.0	15,833.33*	1,15,752	1.31	9.64
Crops + Dairy (1.0 ha)	10,068.4	32,116.67**	1,15,752	3.19	11.27
Crops + Fishery (1.20 ha)	16,352.0	72,045.83*	6,78,350	4.41	41.43

Note: * banana equivalent yield ** maize equivalent yield

Figure 3. Economic water productivity and scale of references in four river basins of Tamil Nadu.



Water Productivity Improvement Measures and Future Challenges

Water productivity could be improved either by reducing the water losses that occur in various ways during water conveyance and irrigation practices or by increasing the economic produce of the crop through efficient water management techniques. Principle factors that influence water losses and water productivity of a command area are the design and the nature of construction of the water conveyance system, type of soil, extent of land preparation and grading, design of the field, choice of irrigation methods and skill of irrigators.

The scale and boundary of the area over which water productivity is calculated greatly affect its value. This is because that the outflow 'losses' by S, P and runoff at a specific location (or field) can be reused at another location within the area under consideration. Data on water productivity across scales are useful parameters to assess whether water outflows upstream are effectively reused downstream. The limited data suggest that water productivities at scale levels vary widely. The paucity of data on water productivity at scale levels higher than the field level is the major constraint (Jacob et al. 2003). In this context, increasing crop water productivity is a challenge at various levels which is briefly outlined below:

The first challenge is to continue to enhance the marketable yield of crops without increasing transpiration. The second challenge is at field, farm and system levels to reduce as much as possible all outflows that do not contribute to crop production. The third challenge is to increase the economic productivity of all sources of water, especially rainwater but also wastewater of various qualities and saline (ground) water. Interdisciplinary team work is warranted.

The study results thus help to derive the following policy recommendations:

a) Introduction of modern water management technologies should be taken up by the extension department of the government and nongovernmental organizations to minimize the wastages.

b) Agricultural technology transfer programs should be strengthened to increase the technical efficiency, which in turn will help increase the rice production further from 25 % to 32 % in the canal irrigation systems.

c) Wherever possible, multiple uses of water should be exploited in order to increase the water productivity.

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Water Productivity of Irrigated Agriculture in India: Potential Areas for Improvement

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Introduction

Economic value of water in agriculture is much lower than that in other sectors (Barker et al. 2003), including manufacturing (Xie et al. 1993). Growing physical shortage of water on the one hand, and scarcity of economically accessible water owing to increasing cost of production and supply of the resource on the other had preoccupied researchers with the fundamental question of increasing the productivity of water use in agriculture in order to get maximum production or value from every unit of water used (Kijne et al. 2003). Raising water productivity is the cornerstone of any demand management strategy (Molden et al. 2001).

Raising crop water productivity means raising crop yields per unit of water consumed, though with declining crop yield growth globally, the attention has shifted to potential offered by improved management of water resources (Kijne et al. 2003). It is necessary to ease water scarcity and to leave more water for other human uses and nature, if we want to reduce the negative consequences of reallocating water to other sectors. But the key to understanding the ways to enhance water productivity is to understand what it means (Kijne et al. 2003). After Molden et al. 2003, the definition of water productivity is scale dependent. Water productivity can be analyzed at the plant level, field level, farm level, system level and basin level, and its value would change with the changing scale of analysis. Many researchers have argued that the scope for improving water productivity through water management, or efficiency improvement, is often over-estimated and the reuse of water is under-estimated (Seckler et al. 2003).

The classical concept of irrigation efficiency used by water engineers omitted economic values and looked at the actual evapotranspiration (ET) against the total water diverted for crop production (Kijne et al. 2003). Moreover, it does not factor in the ‘scale effect’ (Keller et al. 1996). With a greater opportunity to manipulate crop yields without altering consumptive use (ET) and growing cost of production and supply of water, with increased cost of water control to achieve higher physical efficiency in water use, and with growing pressure to divert the water to alternative uses, there have been major advancements in the theoretical discourse on ways to analyze water productivity in crop production. This seems to have led to more comprehensive definitions of water productivity.

Analyzing crop water productivity involves complex considerations and there is no single parameter which could determine the efficiency with which water is used in crop production. The major crop water productivity parameters used in literature are physical productivity of water expressed in kilograms of crop per cubic meter of water diverted or depleted (kg/m^3); net or gross present value of the crop produced per cubic meter of water (Rs/m^3) known either as combined physical and economic productivity of water use or water productivity in economic terms; and net or gross present value of the crop produced against the value of the water diverted or depleted (Kijne et al. 2003).

Although crop production is the major consumptive use of water in many river basins, increasingly there are other competing uses of water, usually with higher returns per unit of water depleted. Therefore, changing inter-sectoral water allocation norms in favor of more efficient uses would result in higher overall basin water productivity, although it is important that existing users are properly compensated. Also, at the level of river basin, opportunities might exist for enhancing crop water productivity by growing certain water-intensive crops in regions where water productivity is greater due to more favorable climatic and agronomic factors (Abdulleev and Molden 2004), indicating the need for inter-regional water allocation.

On the other hand, enhancing water productivity at the field or irrigation system level through water control may adversely affect the availability of water for downstream uses in a closed basin. The reason is the probable reduction in the non-consumptive part of the water applied, along with the reduction in non-beneficial part of the depleted water that can occur due to water control measures. If those downstream uses have a higher return per unit of water use, water control measures would result in productivity losses. Also, at the basin level, regional food security and employment needs would be other important considerations besides maximizing water productivity in crop production. Size of the market would be another consideration for making choices for large-scale shift to high-valued crops that give higher return per unit of depleted water, at the basin scale. Hence, considerations for enhancing basin level water productivity would be different from that for maximizing the farm level and system level water productivity.

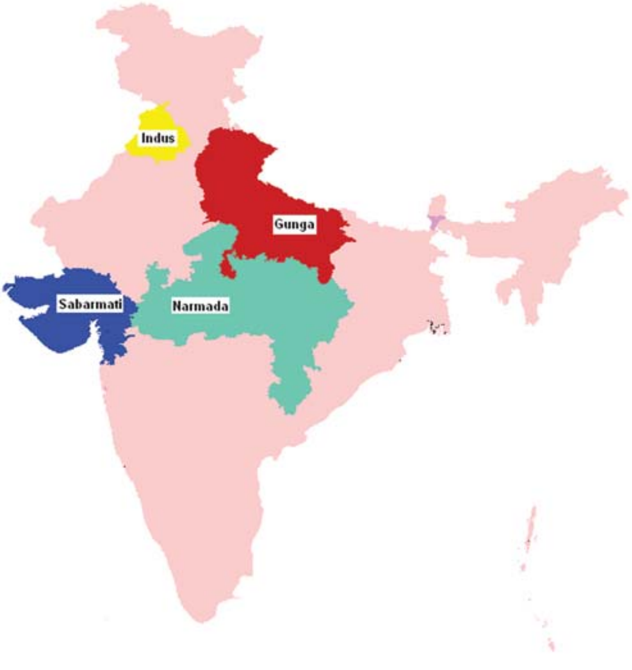
In a nutshell, if one integrates the ‘scale consideration’ and various physical and economic considerations in assessing water productivity, there could be many opportunities and constraints in enhancing water productivity in crop production. The opportunities could come from yield improvements through better agronomic inputs and obtaining greater water control to reduce the ‘depleted water’; diverting the available water to crops that give higher cash return per unit volume of water consumed; growing crops in areas where their ET values are lower; and reducing the amount of applied water which has high opportunity costs whereas the constraints could come from the regional food and employment security concerns, and potential decline in market value of the high-valued crops in the face of surplus production.

Great opportunities exist for enhancing the productivity of water use in agriculture in India. Some of them include: 1) rationing water allocation to ensure meeting the evapotranspirative needs of the plants at the critical stages, which means establishing greater control over timing and the quantum of water delivery; 2) providing appropriate quantum of fertilizer and nutrient inputs to the crops to realize the yield potential; and growing certain crops in regions where the ET requirements are lower and genetic potential of the crop could be realized. What needs to be understood is that while the yield would increase with an increase in actual ET, the water productivity would start leveling off and then start declining much before the yield reaches the maximum (Molden et al. 2003). This means there is a clear trade-off between yield enhancement and water productivity enhancement at higher levels of ET. When water becomes scarce, the irrigation water allocation has to be optimized to get positive marginal productivity.

Objectives, Approach and Methodology

In this study, the scope for water productivity enhancement is analyzed by estimating 1) the incremental changes in irrigation water productivity, and marginal productivity of irrigation water for select crops with increase in irrigation water allocation and fertilizer inputs; 2) the spatial variation in average productivity of crops vis-à-vis agro-climatic regions; and 3) comparative average water productivity with different sources of irrigation which represent different degrees of control over water delivery.

Map 1. Map Showing Study Locations.



The locations and regions in which the study basins are located are shown in shared form in Map 1. The approach used in the study is a case study based using primary surveys. Four river basins in India were selected for the study. They are Indus Basin; Narmada River basin; Ganges Basin and Sabarmati River basin.

The study analyzed water productivity variations across 1) farms within the same type of crops and with the same pattern of irrigation; and 2) irrigation types from wells, canals and conjunctive use; and 3) agro-climates within the same basin. It involved collection of data on parameters governing water productivity in crop production such as cropping system, cropped area, crop inputs (bio and chemical fertilizers, farm labour, irrigation water use, irrigation schedules, and crop technology), crop outputs (main product, by product, market price of crops), and method of irrigation. For each irrigated crop, the sample size is 30-35 for each agro-climate within a river basin. In addition to that, there were samples for each type of irrigation source. Hence, the maximum sample size was 90 in the one location; but limited to only situations where sufficient samples for different modes of irrigation were available.

Data and Sources

Data used for water productivity analysis are primary data from farmers. Data collection was done using a structured questionnaire from locations in all the four basins, viz., Indus, Ganges, Narmada and Sabarmati. From the Indus, only one location was covered; from Ganges also one location was covered; from Narmada, nine locations, each representing one agro-climatic condition, was covered. From Sabarmati, four locations, each representing one agro-climate, were selected. The data collected from farmers included data on crop inputs comprising cost of seeds, labor, fertilizer and pesticides, quantum of irrigation water, and quantity (weight in kg) and market price (Rs/kg) of main and byproducts of the crop output. In addition, the discharge of irrigation wells (liter/sec) was measured using a bucket and stop watch to quantify the volume of water pumped, for which data on number and hours of irrigation concerning each crop and for each season were obtained from the farmers.

Analytical Procedure

The physical water productivity $\sigma_{irri,\, i}$(kg/m^3) and water productivity in economic terms, $\theta_{irri,\, i}$(Rs/m^3) in a purely irrigated crop i are estimated as:

$$\sigma_{irri,\, i} = \frac{\nabla_{irri,\, i}}{1{,}000\Delta_{irri\, ,i\, i}} ; \theta_{irri,\, i} = \frac{NR_{irri,\, i}}{1{,}000\Delta_{irri\, ,i\, i}} \quad ....1, 2,$$

$\Delta_{irri\, ,i}$, and $\nabla_{irri\, ,i}$ are the irrigation water dosage (mm) and yield (kg/ha) for purely irrigated crop$_i$, respectively in mm. $NR_{irri,\, i}$ is the net return per unit area of the crop (Rs/ha). All winter crops selected for the study are treated as purely irrigated crops, and the green water use for these crops was ignored. The reason is that their yields under un-irrigated condition as well as residual soil moisture before sowing are negligible. All crops covering two seasons, viz., *kharif* and winter, having no rain-fed yields were also treated as irrigated crops. Winter wheat in Narmada Basin, cotton in West Nimar in the Narmada Basin, winter wheat in Uttar Pradesh (UP), Punjab, and all crops selected from Sabarmati basin (namely, wheat, castor, bajra and cotton) were treated as irrigated crops and, therefore, the water productivity values estimated for them are irrigation water productivity[1].

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[1] In areas with moderate rainfall like eastern UP, this must have resulted in over-estimation of irrigation water productivity.

Marginal physical productivity of water, $\sigma_{comb\text{-}irri,\,j}$(kg/m^3), and marginal water productivity in economic terms $\theta_{comb\text{-}irri,\,j}$(Rs/m^3) for crops, which receive supplementary irrigation, and having rain-fed yields, with respect to irrigation, are estimated as:

$$\sigma_{comb\text{-}irri,\,j} = \frac{\nabla_{comb\text{-}irri,\,j}}{1{,}000\Delta_{comb,j}} \;;\; \theta_{comb\text{-}irri,\,j} = \frac{NR_{comb\text{-}irri,\,j}}{1{,}000\Delta_{comb,j}} \quad \text{.................3, 4,}$$

Where, $\nabla_{comb\text{-}irri,\,j}$ is the yield corresponding to irrigation water applied (kg) and $\Delta_{comb,j}$ is the irrigation water applied for the crop j (mm). $NR_{comb\text{-}irri,\,j}$ is the net return per unit area corresponding to the irrigation water applied for the same crop (Rs/ha). $\sigma_{comb\text{-}irri,\,j}$ and $\theta_{comb\text{-}irri,\,j}$ were obtained by running a regression of yield and net returns from the crop against irrigation water applied for each crop, respectively. The regression coefficients give the marginal physical productivity of water and water productivity in economic terms, respectively, of irrigation for these crops. This gives the mean value of marginal water productivity for all the farmers growing that crop. One major assumption involved in this analysis is that the water application is still in the scarcity regime, meaning the total consumptive use may fall short of or just meet the evapotranspirative demands. Therefore, the response curve of yield and net return to irrigation water use were treated as linear. This no way means that the volumetric water applied (effective rainfall and irrigation) is below ET demand, as farmers can provide excessive irrigation in certain periods of the crop season, resulting in losses.

The marginal water productivity of irrigation water for individual farmers were estimated by subtracting the ‘a’ coefficient , i.e., Y intercept, of the regression equation for yield and net return, respectively, from their corresponding crop yield and net returns, and dividing by the volume of irrigation water applied. Paddy from Jabalpur and Mandla in Narmada River basin was considered for this methodology, as it had rain-fed yield in many locations.

The drivers of change in water productivity were analyzed by running regressions of crop yield (dependent variable) against irrigation dosage and fertilizer dosage (as separate independent variables) for select crops (viz., wheat and cotton); and crop water productivity in economic terms against fertilizer dosage and irrigation water dosage for the same crops.

Field Level Water Productivity: Results from Four Indian River Basins

There are several studies done over the past 2 years analyzing water productivity in irrigated production covering many heterogeneous physical settings in India, in terms of agro-climate and overall water resource availability and quality. The locations included part of Indus Basin in south-western Punjab; part of Ganga Basin in eastern Uttar Pradesh; and different locations in Sabarmati River basin in Gujarat. The studies included analyses of the productivity of irrigation water for several crops from both physical and economic point of view. All the analyses are based on well-irrigated crops and the volume of applied water was used in the denominator of water productivity.

The results of the analyses are presented in summary form in Table 1 to Table 2 to highlight the variations in water productivity with the same location across farmers; and across locations within the same basins; and across basins for the same crop. The irrigated crops considered for the analyses are winter wheat (Punjab, UP, Gujarat, and Madhya Pradesh); and *kharif* paddy in Punjab, UP, Gujarat, Madhya Pradesh.

As Table 1 shows, there are major variations in water productivity across farmers within the same location. This is not only restricted to water productivity in economic terms, but also to the physical productivity of water use. For instance, in the case of Batinda in Punjab, the data on water productivity in wheat were analyzed for 80 farmers and the variations are remarkable. The physical productivity of water varies from 1.29 kg/m^3 to 4.27 kg/m^3. The water productivity in economic terms ranges from a lowest of Rs.1.25/m^3 to a highest of Rs.13.35/m^3.

Table 1. Irrigation water productivity in wheat in three river basin locations in India.

Name of the basin	Name of the region	Name of the district	Physical productivity (Kg/m^3)		Water productivity in economic terms (Rs/m^3)	
			Average	Range	Average	Range
Narmada	Central Narmada valley	Hoshangabad	0.91	0.43 – 1.60	2.31	0.034 – 7.48
		Jabalpur	0.47	0.23 – 0.88	1.06	0.022 – 4.66
		Narsingpur	0.53	0.26 – 0.75	1.11	0.006 – 3.52
	Jhabua hills	Jhabua	0.60	0.38 – 0.88	1.20	0.05 – 11.58
	Satpura plateau	Betul	0.84	0.52 – 2.06	2.61	0.10 – 10.21
	Malwal plateau	Dhar	1.05	0.64 – 1.80	2.04	0.072 – 6.67
	Nimar plain	West Nimar	0.83	0.52 – 1.62	1.99	0.012 – 7.60
	NHRCh	Mandla	1.80	0.98 – 2.95	4.09	0.21 – 10.79
	Vindhya plateau	Raisen	1.01	0.61 – 1.58	2.27	0.25 – 7.67
Indus	South-Western	Batinda Punjab	2.33	1.29 – 4.27	5.93	1.25 – 13.35
Ganges	Eastern Uttar	Varanasi Pradesh	2.61	1.65 – 4.98	10.80	5.02 – 24.51
Sabarmati	North Gujarat, Western India	Sabarkantha (Bayad)	2.75		8.9	
		Sabarkantha (Himmatnagar)	0.80		2.3	
		Ahmedabad	0.71		1.1	
		Kheda	1.71		4.88	

Source: Authors' own analysis based on primary data

Note: NHRC: Northern Hill Region of Chhattisgarh

As regards variations in water productivity across regions within the same basin, Narmada is the most illustrative example. Within Madhya Pradesh part of Narmada Basin, wheat is grown in all the seven agro-climatic regions that fall inside the basin, and is a purely irrigated crop in the sense that it is not possible to grow this crop just using the soil moisture available after the rains, irrespective of the high magnitude of monsoon rains available in certain regions. Data on irrigation water productivity were available for as many as 45 farmers from each location. Hence, comparison of water productivity in wheat highlights the potential variation in water

Table 2. Marginal productivity of irrigation water in paddy in three selected river basins in India.

Name of the basin	Name of the region	Name of the district	Physical productivity (Kg/m^3)		Water productivity in Economic terms (Rs/m^3)	
			Average	Range	Average	Range
Narmada	Central Narmada valley	Jabalpur	1.62	0.85 – 2.57	3.95	0.05 – 10.28
	NHR.C	Mandla	2.13	1.20 – 4.00	1.43	0.43 – 7.74
Indus	Punjab	Batinda	3.69	3.17 - 4.36	10.57	4.47 – 24.94
Ganga	UP	Varanasi	2.54	1.21 – 3.96	4.90	0.94 – 11.89
Sabarmati	North Gujarat,	Sabarkantha	0.42		0.91	
	Western India	Ahmedabad	1.06		3.34	
		Kheda	0.92		2.98	

*Source:*Authors' own analysis based on primary data collected from the three basin areas

Note: NHRC: Northern Hill Region of Chhattisgarh

productivity possible for irrigated crops. The average physical productivity of irrigation water in wheat ranges from 0.47 kg/m^3 in Jabalpur to 1.8 kg/m^3 in Mandla.

Also highly significant are the water productivity variations across the four river basins, viz., Indus, Ganges, Narmada and Sabarmati. This could be the result of variations in water availability situation, agro-climate and the level of agricultural development. First of all, Indus is a physically water-scarce river basin; so is Sabarmati, and are all 'closed' basins, wherein all the surface water resources are diverted for various uses within the basin and are fully depleted, and additionally, the groundwater resources in these basins are also fully utilized. Narmada Basin still has unutilized water resources, particularly surface water. Agro-climatically, south western Punjab has arid climate; MP part of Narmada has climatic conditions varying from sub-humid to semi-arid. Finally, the degree of the adoption of crop technologies varies from basin to basin. While Punjab is known for progressive farmers, and a high level of adoption of green revolution technologies and high agricultural productivity, Madhya Pradesh's agriculture is relatively very backward. The adoption of modern farming technologies, including irrigation is quite recent in MP. The average water productivity of wheat ranges from a lowest of 0.47 to a highest of 1.8 kg/m^3 in Narmada Basin to 2.33 kg/m^3 in Batinda, Punjab (Indus) to 2.61 kg/m^3 in Banaras, UP (Ganges).

The variations in physical productivity of water across farmers within one location; across different locations within a basin; and between basins result in a higher degree of variation in the productivity of water use in economic terms as shown in last columns of Table 2. While the ratio of the highest and the lowest values of physical productivity is 3.0 in eastern UP in Ganges, the corresponding ratio for combined physical and economic productivity is 4.8 for the same location. While the ratio of the highest and the lowest values of physical productivity of irrigation water in wheat is 3.25 in south-western Punjab in the Indus, the corresponding value for water productivity in economic terms for the same location is 12.6. The ratio of average physical productivity of irrigation water in wheat across basins is 1.45 (3.69/2.54) and when south western Punjab and eastern UP are compared, the corresponding ratio for combined physical and economic productivity is 2.15 (10.57/4.90).

Determinants of Water Productivity Variations

Increasing of fertilizers and nutrients increases the crop yields up to a point but the physical productivity of water can be manipulated without any change in irrigation inputs. With the same amount of water applied, the crop consumptive use would change depending on the timing of water. Optimum water application can ensure full utilization of the applied water for evapotranspirative demand. Non-availability of moisture at critical stages of crop growth can significantly reduce the crop growth and yield and the reduction would not be proportional to the reduction in water applied or water consumed. Therefore, the quality of irrigation (reliability and adequacy) should affect water productivity, with the same amount of irrigation water applied. However, against this, plants have highly developed adaptive mechanisms to compensate for water stress in different growth stages, and the only way to factor these in properly is to use a well calibrated crop growth model, or through the development of crop production functions. Similarly, the same crop would have different water requirements under different climates and, therefore, different water productivity levels with the key inputs such as fertilizers, labor and irrigation remaining the same.

While labor and fertilizers and nutrient inputs can help enhance the crop yield and physical productivity of water, the economic productivity could decrease, as the marginal increase in yield and gross return may not keep pace with the marginal increase in input costs to achieve such high levels of yield beyond a point (Barker et al. 2003). Hence, water productivity in economic terms is important for assessing the efficiency with which water is used in crop production.

Water productivity can also be enhanced by reducing the amount of non-beneficial depletion of applied water in the field, through water control. Water control is to enable the supply of water close to the difference between crop water requirement, and available soil moisture in the root zone. The measures for this include on-farm water management practices, improving the conveyance of water. Micro-irrigation systems take care of water control for many crops, and in certain other crops by farm leveling. We would demonstrate the impact of these factors on changing the key determinants of water productivity and water productivity as such.

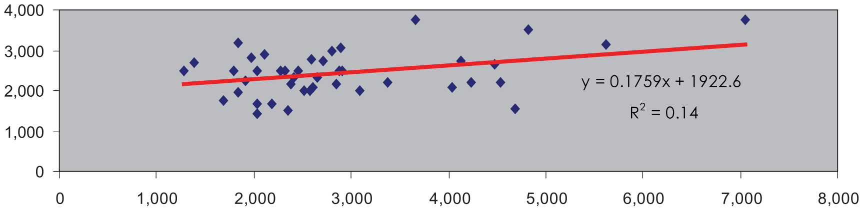
Identifying the Causes of Productivity Variations Across Farmers

In order to analyze the variations in yield and water productivity across farmers, the data collected from four agro-climatic regions in Narmada River basin were analyzed. The analysis included the following: 1) the crop yield response to irrigation water applied; 2) the water productivity (Rs/m^3 of water applied) response to irrigation; 3) the yield response to fertilizer use; and 4) the water productivity response to fertilizer application.

Responses of Yield and Water Productivity to Applied Water

In the case of Hoshangabad District, data of applied water, fertilizer dosage, crop yield, and water productivity in economic terms (estimated) were available for two consecutive years, viz., 2002 and 2003. The regression analysis showed that the relationship between the dosage of irrigation water and yield for winter wheat of 2002 is linear. The R square value here is only 0.14, and hence the relationship is not strong. As shown in Figure 1, wheat yield responded to increase in the dosage of irrigation water and for the same level of irrigation, the yield

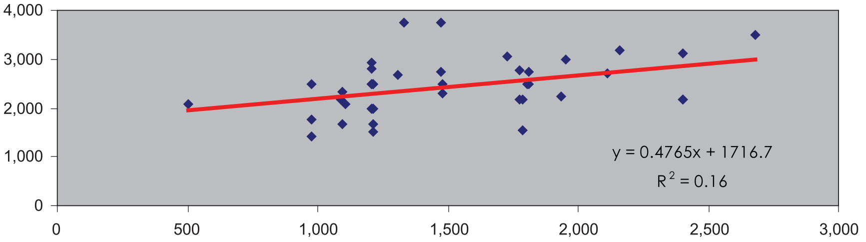
Figure 1. Yield vs. irrigation dosage in wheat in Hoshangabad in 2002.



differences across farmers are quite substantial. This can perhaps be explained by the differential levels of fertilizer use by these farmers, differences in soil quality, changes in date of sowing, and differences in crop variety.

Figure 2 shows the graphical representation of the variation in yield with differential levels of fertilizer input. It shows a slightly stronger relationship between fertilizer use and crop yield (R^2=0.16). Higher dosage of fertilizer meant higher wheat yield. But, this does not mean that it is the higher fertilizer dosage which causes higher yield. Generally, it is the farmers who have good irrigation facilities and use a higher quantum of irrigation water who use a proportionally higher dose of fertilizers. Due to this co-linearity between irrigation and fertilizer dosage, the increase in yield cannot be attributed to higher dosage of fertilizers. Hence, in order to segregate the effect of fertilizer dose on crop yield, a more thorough examination of data was carried out.

Figure 2. Yield vs. fertilizer dosage in Hoshangabad in 2002.

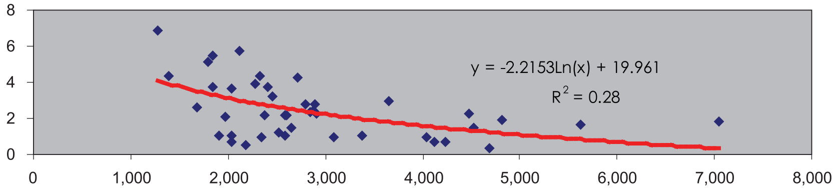


It was found that two farmers applying the same dosage of irrigation (1,834 mm) applied different quantities of fertilizers (worth Rs.1,213/ha and Rs.2,160/ha, respectively) and got different levels of yield (19.8 quintals/ha and 31.7 quintals/ha, respectively). In another case, two farmers applied the same dosage of irrigation (2,035mm), but applied fertilizers in varying doses (worth Rs.975/ha and Rs.1,205/ha respectively), and got different yields (1,480 kg/ha and 2,500 kg/ha respectively).

Figure 1 also meant that many of the farmers are applying scarcity irrigation and could have actually got higher yield had they applied higher dozes of irrigation with proportional increase in fertilizer inputs. But, the amount of water applied to the soil also influences the nutrient absorption capacity of the plants and, therefore, irrigation water shortage might be limiting farmers' ability to apply adequate quantities of fertilizers. By and large, the maximum yield corresponded to maximum irrigation.

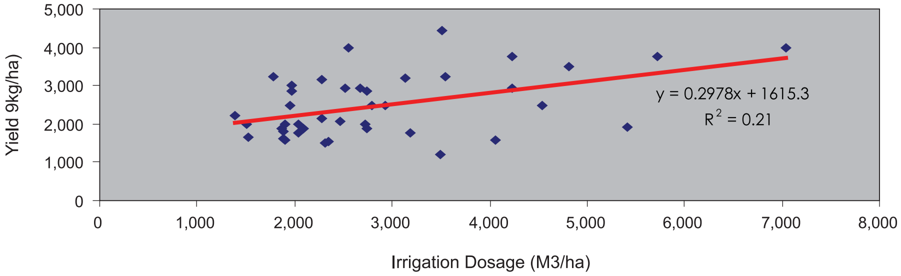
The graphical representation of water productivity response to irrigation is given in Figure 3. The relationship is inverse and exponential. Higher dosage of water applied meant lower water productivity (R^2= 0.28). Generally, those who applied higher dosage of water had lower levels of water productivity, while many farmers who applied lower dosage of irrigation (200 to 225 mm of irrigation) got high water productivity. At the same time, many farmers who maintained similar dosage of irrigation got much lower water productivity (Rs/m^3), which could be due to the low levels of fertilizer inputs, which reduced the crop yields significantly. The lower water productivity at high dosage of irrigation could be due to lack of proportional increase in yield, increase in cost of fertilizers which reduces the net returns, and increase in volume of water applied, which increases the value of denominator.

Figure 3. Water productivity vs. irrigation dosage in wheat in Hoshangabad in 2002.



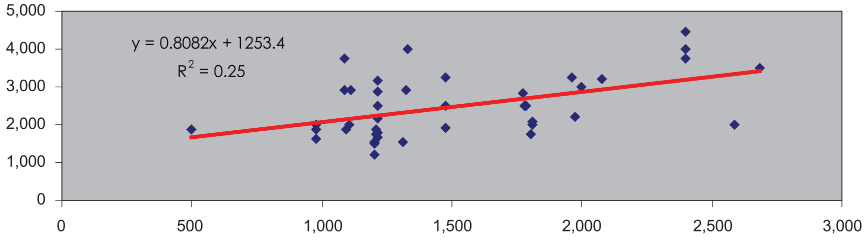
The analysis was repeated for the year 2003. It showed a stronger positive linear relationship between applied water and crop yield in wheat (R^2=0.21). Higher levels of water dosage generally ensured higher yield (Figure 4). The incremental yield due to increase in dosage of irrigation water by 100 mm was around 230 kg/ha. But, there were significant yield differences between farmers who applied more or less the same amount of water. This could be explained by the factors mentioned above. Nevertheless, slightly improved relationship better fertilizer and irrigation dosage (with an R square value of 0.25) confirms this (Figure 5).

Figure 4. Yield vs. irrigation in wheat in Hoshangabad in 2003.



The regression values for the response of yield to irrigation dosage being very small (Figure 1 and Figure 4), one could argue that many factors other than irrigation explain yield variations. But, given the fact that the data that are being presented here are for different farmers, who represent different soil conditions, different planting dates and different seed

Figure 5. Yield vs. fertilizer dosage in wheat in Hoshangabad in 2003.

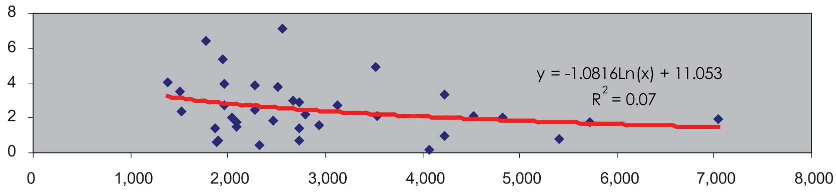


varieties, all of which having a potential to influence the crop yield, the relationship and regression coefficient is significant[2]. Also, the slope of the yield curve is very mild in the case of Figure 3, which is quite contrary to what can normally be found given the wide range in irrigation water dosage among the sample farmers.

The regression between water dosage and water productivity (Rs/m^3) showed a poor inverse relationship between the two unlike what was found for 2002 (Figure 6). This could be due to the reasons explained above for the same crop grown during 2002. Some of the farmers who were in the lower range of irrigation dosage (between 200 mm and 300mm) got very low water productivity values (between Rs.0.41/m^3 and Rs.1.38/m^3), whereas some other farmers got values of approximately Rs.7/m^3 of water. This could be due to the wide differences in fertilizer dosage, which resulted in differential yields. The strong linear relationship between fertilizer dosage and crop yield (R^2=0.25) as shown by Figure 5 is a testimony to this.

A closer look at the chart showing relationship between irrigation dosage and crop yield also provides better clues to this effect. There are many examples of farmers applying more or less the same dosage of irrigation, but applying different dosage of fertilizers and getting different levels of yield. For instance, two farmers who applied irrigation dosages of 2,518 and 2,557 m^3 of water to their wheat, applied different levels of fertilizers (worth Rs.1,112/ha and Rs. 2,400/ha) and in turn got yields of 2,910 kg/ha and 4,000 kg/ha, respectively.

Figure 6. Water productivity vs. irrigation dosage in wheat in Hoshanganad in 2003.



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[2] With changing soils, the nutrient levels could change. With changing planting dates, the soil moisture availability could change; so the crop water requirement and yield potential. Yield potential could also change with seed variety.

The analysis was repeated for another region, west Nimar in Narmada Basin, for cotton in 2003. After the rainy season, the crop is normally irrigated. The yield response to irrigation was polynomial (Figure 7), with yield increasing up to a point (from 100 mm to 300 mm), and then declining. Many farmers who applied close to 300 mm got the highest yields. Beyond 300 mm, the yield started declining. The curve showing the water productivity (Rs/m^3) response of irrigation dosage (Figure 8) is again 'polynomial'. With increase in dosage of irrigation, while the yield increased, the water productivity did not get affected much. But, beyond the point where the yield was optimum, increase in irrigation dosage led to declining water productivity. This is the third set of response curves.

Figure 7. Yield vs. irrigation water dosage in cotton in West Nimar in 2003.

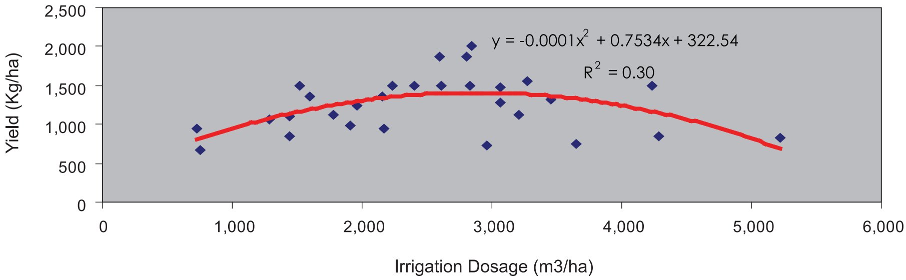
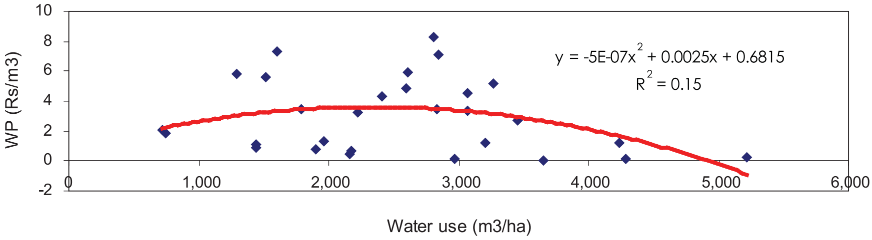


Figure 8. Water use vs. water productivity in cotton in West Nimar in 2003.



Yield and Water Productivity Response to Fertilizer Dosage

As regards yield response to fertilizer inputs, in the case of wheat in Hoshangabad, it was found that the response is extremely weak for the drought year (2002) as shown in Figure 2 (R^2=0.16). At the same time, the response was reasonably good for the normal year 2003 (R^2 =0.25) as shown in Figure 5. Water productivity was also higher for farmers who applied higher dosage of fertilizers (R^2=0.27) during the season of 2003, though such trends were not seen for the drought year of 2002. Such a response does indicate that the farmers are optimally using fertilizers and irrigation water to enhance the returns.

In the case of cotton in West Nimar, water productivity response curve for fertilizer dosage was found to be 'polynomial' for the drought year (2002), with productivity (Rs/m^3) increasing from the lowest values at low levels of fertilizer use towards the middle range, and then declining (R^2= 0.11). Such a response curve could be explained as resulting from very high doses of fertilizers generally accompanied by an increased dose of irrigation water. Higher dosage of irrigation water could also increase the chances of fertilizer leaching, reducing the nutrient intake by the plants and flattening the response curve of yield. At the same time, the yield gains obtained due to the same were not significant enough to offset the effect of increased cost of inputs, and increase in the volume of water applied. This is quite natural as the farmers are interested in maximizing the returns per unit of land, and not water.

Analyzing the Changes in Water Productivity Due to Changes in Quality and Reliability of Irrigation

There is not much empirical evidence available from across the country to provide evidence to the effect that greater reliability of irrigation water supplies and control over water allocation leads to greater water productivity.

Analysis from groundwater irrigated areas of North Gujarat showed that the gross returns per cubic meter of applied water were higher for shareholders of tubewell companies, when compared with that of farmers who were buying water from well owners. The gross water productivity was Rs. 5.61/m^3, as against Rs.4.61/m^3 for water buyers. The gross returns only indicate the physical efficiency of water use, as it does not take into account the input costs, and only converts the main product and by-product into cash equivalents. The difference between the two is in the 'terms of irrigation services'. In the case of shareholders, the entitlement of water is fixed in volumetric terms, and water supply is highly reliable. In the case of water buyers, the well owner supplies enough water to make sure that the cultivator gets sufficient yield as his irrigation charge is paid in proportion to the total crop yield.

The difference between the two cases is in terms of water allocation norms and the reliability of water supply. In the case of shareholders, supply is rationed and known to the farmers much in advance of the season. Hence, they are able to do proper water budgeting and apply optimum dosage of fertilizers whereas the farmers who purchase water on hourly basis are at the mercy of the well owners. They do not try to optimize fertilizer dosage, and go for the best quality seeds, as they are not sure of getting adequate water supplies. This reinforces the fact that net return from crop production is less elastic to the cost of irrigation than the reliability of irrigation.

Yields in two major crops, viz., wheat and paddy in three different types of irrigation systems, which represent three different degrees of water control, in two different regions of Bist Doab area in Punjab were compared to understand the impact of differential quality of irrigation water. The three systems selected are canal irrigation, well irrigation and conjunctive use. The underlying premise in the analysis is that farmers using canal water do not have complete control over irrigation and, hence, will not be able to apply water at critical stages in right quantities. On the other hand, farmers using well water, despite incurring higher costs in terms of capital, would be able to apply water to their crops as and when they require, subject to the availability of electricity. As farmers using both canal water and well water should have a higher degree of control over water application compared with that of canal irrigators, the 'overall quality of irrigation' would depend on what proportion of the total demand is met from canals, and what proportion is met from groundwater.

But, analysis involved comparing water productivity in wheat under different sources of irrigation in two distinct agro-ecological regions. This was because an adequate number of irrigators for each of the three sources of irrigation was not available from the same agro-ecological region. The first is lower Bist Doab area, with low rainfall and semi-arid climate; and the second, the sub-mountainous region with medium to high rainfall with sub-humid climate. Comparison of yield with different sources of irrigation could be made between conjunctive use and canal water (in sub-mountainous region). The analysis showed that yield figures are the lowest for farmers using only canal water for both paddy and wheat, and the second lowest for farmers using both canal water and groundwater (Table 3). The farmers using well water (in Jalandhar and Kapurthala) were found to be getting the highest yield. The yield differences are quite substantial between categories within the region and across regions. While agro-ecology would be an important factor affecting the crop yields, such large differences in yield could only be explained by the quality and reliability of irrigation water.

Table 3. Differential land productivity with varying quality of irrigation in Punjab.

Name of region	Name of district	Predominant source of irrigation	Crop yield (ton/ha)	
			Paddy	Wheat
Lower Bist Doab	Jalandhar	Well water	6.26	4.68
			5.20	4.40
	Kapurthala	Well water	5.98	4.73
			5.52	5.30
Sub Mountainous	Hoshiarpur	Conjunctive use	4.46	3.82
			4.65	3.79
		Canal water	2.77	3.52
			3.47	2.80

Source: Authors' own analysis using primary data

Analyzing Water Productivity Variations across Regions Due to Climatic Advantages

Spatial analysis of water productivity of selected crops carried out for nine districts in seven agro-climatic regions in Narmada Basin are presented in Table 4. The spatial analysis of water productivity is an important aspect of the strategy to enhance water productivity at the agro-climatic level (Kijne et al. 2002), as productivity of applied water is a function of agro-climate. Both physical productivity and water productivity in economic terms is determined by the climatic conditions, which determines the actual consumptive water requirements, and the availability of soil moisture from precipitation. In regions, with favourable climatic conditions, the biomass output per unit of water evapotranspired would be higher as in regions with less favorable climate. Here, we have compared water productivity of wheat and paddy which are two significant crops.

The physical productivity of applied water for grain production during the normal year was estimated to be the highest for northern hill region of Chhattisgarh in Mandla District (1.80 kg/m^3) although Raisen District in the traditional wheat-growing belt and it was the lowest for Jabalpur in Central Narmada Valley (0.47 kg/m^3). This is mainly due to the major difference in irrigation water applied, which is 127 mm against 640 mm for Jabalpur. This is a significant difference, with the highest being 250 % more than the lowest. The difference in irrigation can be attributed to the difference in climate between Jabalpur (dry semi-humid) and Mandla (moist sub-humid), which changes the crop water demand. It can also be noted that the physical productivity in the normal year is the second highest in Raisen (1.01 kg/m^3). Higher biomass output per unit volume of water (physical productivity) should also result in higher economic output especially when the difference is mainly due to the climatic factors, which change the ET requirements, unless the factors which determine the cost of inputs significantly differ. In our case, it was found that the net economic return per cubic meter of water was the highest for the same region for which physical productivity was higher (Rs. 4.09/m^3), followed by Raisen (Rs. 2.77/m^3). But the same was the lowest for Narsingpur (Rs. 0.86/m^3), which had the second lowest physical productivity.

The difference between gross and net water productivity (furnished in Table 4) is that in the first one, the total economic value of outputs from unit area of outputs is only considered in the numerator, whereas in the second case, the net income from crop production after deducting the cost of inputs per unit area is considered.

Table 4. Region-wise irrigation water productivity (wheat) and marginal productivity of irrigation water (paddy) in Narmada River basin for selected crops.

Name of the region	Name of the district	2002-03 (Drought year)				2003-04 (Normal year)			
		Physical productivity (Kg/m^3)		Water productivity in economic terms (Rs/m^3)		Physical productivity (Kg/m^3)		Water productivity in economic terms (Rs/m^3)	
		Main product	By-product	Gross	Net	Main product	By-product	Gross	Net
				Wheat					
1. Central Narmada Valley	Hoshangabad	0.81	0.81	5.74	2.09	0.91	0.90	6.25	2.31
	Jabalpur	0.44	0.43	3.08	0.89	0.47	0.46	3.42	1.06
	Narsingpur	0.53	0.49	3.84	1.11	0.49	0.47	3.47	0.86
2. Jhabua Hills	Jhabua	0.73	0.65	5.32	1.38	0.60	0.55	4.69	1.20
3. Satpura Plateau	Betul	0.72	073	5.34	2.14	0.84	0.82	6.05	2.61
4. Malwal Plateau	Dhar	1.07	1.02	8.05	2.46	1.05	1.05	7.67	2.04
5. Nimar Plain	West Nimar	0.85	0.83	6.65	2.38	0.83	0.83	6.20	1.99
6. NHRC	Mandla	0.92	0.88	6.62	1.44	1.80	1.78	12.75	4.09
7. Vindhya Plateau	Raisen	0.77	0.77	5.33	2.00	1.01	1.01	6.82	2.77
				Paddy					
1. Central Narmada Valley	Jabalpur	1.08	0.79	5.86	1.99	1.62	1.15	9.36	3.95
2. NHRC	Mandla	1.74	1.26	11.69	2.12	2.13	1.59	12.50	1.43

Source: Authors' own analysis based on primary data

Note: NHRC: Northern Hill Region of Chhattisgarh

As regards paddy, there are only two regions which irrigate paddy. The physical productivity for grain during the normal year was estimated to be higher for northern hill region of Chhattisgarh in Mandla District (2.13 kg/m^3) whereas it was only 1.62 kg/m^3 in Jabalpur District of Central Narmada Valley. Likewise, water productivity in economic terms was found to be higher for northern hill region of Chhattisgarh (Rs.3.95/m^3) as against Rs.1.43/m^3 for Jabalpur in Central Narmada Valley. Similar figures were found for the drought year (2002) in which the physical productivity of applied water was 1.74 kg/m^3 in Mandla against 1.08 kg/m^3 in Jabalpur.

Spatial analysis of water productivity in three agro-climatic regions of Sabarmati Basin showed that there is significant variation in physical water productivity and water productivity in economic terms (gross and net) of irrigation water across different agro-climatic regions for all the four crops selected from Sabarmati River basin. For instance, water productivity in physical terms for wheat ranged from 0.71 kg/m^3 in Daskroi to 2.75 kg/m^3 in Bayad. The water productivity in economic terms (gross) ranged from Rs. 4.66/m^3 in Daskroi to Rs. 18.39/m^3 in Bayad. The net water productivity for wheat for the same locations ranged from Rs. 1.38/m^3 to Rs.4.66/m^3. Similar variations in physical productivity of water were found for castor oil between Himmatnagar and Kapadwanj. The physical productivity of water ranged from 0.66 kg/m^3 to 1.62 kg/m^3. The gross economic water productivity ranged from Rs. 9.69/m^3 in Himmatnagar to Rs. 25.57/m^3 for Bayad. The net economic water productivity ranged from Rs. 3.56/m^3 in Himmatnagar to Rs. 16.4/m^3 for Bayad. Interestingly, unlike in the case of wheat which gave the highest physical productivity of water and also gave the highest water productivity in economic terms, in case of castor oil, the locations which gave the highest economic water productivity did not coincide with those of the highest physical productivity of water.

Ways to Enhance Irrigation Water Productivity in Economic Terms

Improving Water Control and Its Potential Impact

The analyses presented in the earlier sections clearly show that water productivity is a function of applied water; and dosage of fertilizers, and that it can be manipulated through water control. It is based on the premise that in many situations farmers do not have control over water delivery and fertilizer dosage, or else are tempted to apply more water to maximize the yields and returns per unit of land. The lack of control over water delivery could be either due to lack of physical control over water delivery or due to lack of sufficient water to irrigate. The tendency to apply water or fertilizer in the low productivity regime could be due to two reasons:

1) Farmers are not able to make correct judgments about water allocation for maximizing the aggregate returns (which is the multiple of net returns per ha of the crop, and total area of the irrigated crop), due to lack of correct information about the levels of irrigation that result in the maximum net return per unit of land, and which enables maximizing the area irrigated.

2) Farmers are not confronted with either marginal cost or opportunity cost of using excess water.

In the process, they are not able to get optimum level of yield that gives the highest water productivity.[3] To what extent 'water control' interventions would help enhance water productivity depends on the shape of the yield and water productivity response curves of the crop in question to irrigation inputs. It would also depend on what fraction of the applied water is actually used for non-beneficial depletion from the crop land. We do not have any information about non-beneficial depletion from the applied water. But the major sources of non-beneficial depletion are a) the deep percolation, which is either lost in the vadose zone,[4] or which joins the saline aquifer; b) the evaporation of soil moisture after crop harvest during the fallow period; c) direct evaporation from the soil surface, especially during crop establishment and d) possibly unnecessary watering at the end of the season when it does not contribute to the yield.

We have seen three different types of responses of yield and water productivity to irrigation dosage. We discuss the strategy for enhancing WP in each of these cases. In the first situation: a) the relationship between applied water and yield is positive, but weak; and b) the response of water productivity to applied water is inverse and exponential. In such situations, the reduction in dosage of irrigation water would not affect the yield significantly; and the effect often may not even be adverse. But the same would enhance water productivity significantly. But, this strategy would work only if there is sufficient amount of arable land, which remains uncultivated due to shortage of water. The reason is the water saved from the field can be diverted to expand the area under irrigation.

The second situation is one in which the relationship between applied water and yield is strong and positive, wherein most farmers are applying water under scarcity regime and very few under water abundance regime (Figures 4, 5 and 6). Then, it is likely that with an increase in dosage of irrigation, the physical productivity of water also might increase slightly. But, the water productivity (Rs/m^3) response to applied water is 'inverse-logarithmic'. Here, the best strategy for most of the farmers would be to minimize the irrigation dosage, which would help obtain the highest water productivity in economic terms. Here, it may be necessary for the farmers to expand the area under irrigation slightly to maintain the net returns.

In the third situation, the relationship between applied water and yield is 'polynomial', where yield increases with irrigation dosage up to a certain point, and then declines. This is the situation found in the case of irrigated cotton in West Nimar District (based on Figure 7). In such a case, with increasing dosage of water, the productivity would decline abruptly beyond the point which corresponds to the maximum yield. Hence, the relationship between applied water and water productivity is 'polynomial'. This is the most ideal situation where those farmers who are losing on the yield and income returns have an incentive to reduce irrigation dosage, by which they could enhance both yield and water productivity. The reason why it occurs is the zero marginal cost of electricity used for groundwater pumping owing to the flat rate system of pricing electricity in all the groundwater irrigated states. This mode of pricing creates no

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[3] It is also to be noted that water productivity is not an objective for farmers to realize when water is in plenty. On the contrary, they would try to maximize the income returns per unit of land, for which crop yield (kg/ha) enhancement is the best route.

[4] The water which is 'lost in the vadose zone' normally becomes non beneficial E or ET as bare soil evaporation or transpiration through other (non-productive) vegetation.

incentives for farmers to use groundwater efficiently. In such situations, it is not even necessary that farmers expand the area under irrigation to maximize their aggregate returns from farming. But, there are many farmers who are not getting optimum yield and water productivity due to inadequate dosage of irrigation water. It is important for them to reduce the area under irrigation while increasing irrigation dosage to optimize yield and water productivity.

There are many water allocation and control measures to improve water productivity. Water control is possible through either of the two methods: 1) micro-irrigation technologies, mainly for non-field crops; and, 2) establishing water delivery control devices such as storage systems, particularly in the case of surface irrigation systems where water delivery through tertiary canals is not regular. Micro-irrigation systems can help achieve two things: a) improving control over applied water; and b) reducing the non-beneficial depletion of the applied water and maximizing the consumptive use fraction of the applied water. The potential impact of the second intervention would be in limiting the amount each time. This, in a way, also may help reduce non-beneficial depletion but its impact may be less significant as compared with micro-irrigation.

But, we have not come across situations where farmers are not able to secure optimum levels of water productivity due to water shortages. Farmers have reasonably high degree of control over water delivery as they are all well-owners, power supply being the only factor that reduces the control over water delivery. In states such as Punjab, Gujarat and Madhya Pradesh, the quality of power supply in agriculture is poor. The supply is provided in rotations, and sometimes during night hours. They tend to apply heavy doses of water when power supply is available. This may be leading to a situation where the water productivity starts declining as found in most cases, or yield (Rs/m^3) itself starts declining.

It is quite understandable that farmers do not care about water productivity much. This is in spite of the fact that water availability is extremely limited in some of the areas we have covered in our study like west Nimar and Dhar. Hence, the option of ‘controlling applied water dosage’ for enhancing water productivity would work only in areas where a good part of the cultivable land is kept fallow due to water shortage.

Now, let us look at the option of micro-irrigation. For a given amount of nutrient inputs, the only determinant of the crop yield is the consumptive use of water by the crop (ET) and how far the transpirative requirements of the crop area met during critical stages of crop growth. Using micro-irrigation for row crops, the non-beneficial depletion of applied water could be reduced to nil. Such non-beneficial depletion under traditional method of irrigation would be significant in the case of row crops. Therefore, the twin-objective of achieving higher water productivity and higher yield is possible through micro-irrigation devices. The response curve of yield (Kg/ha) and water productivity in economic terms (Rs/m^3) to irrigation dosage under traditional irrigation and micro-irrigation is given in Figure 9.

It shows that the yield corresponding to the same amount of ‘applied water dosage’ would be higher under micro-irrigation. Or in other words, for the same amount of applied water, the yield would be higher. Research in many parts of India had already shown that for cash crops, particularly those grown in rows such as cotton, the net incremental returns for drip irrigation plots over flood irrigated plots are higher than the sum of capital and operational costs of drip systems.[5] This means that even in situations, where the entire land is irrigated,

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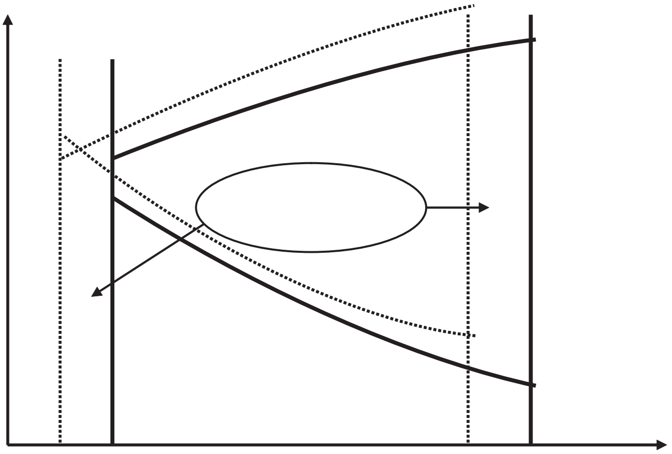
[5] Such crops include banana, sugarcane, orange, grapes and cotton.

Figure 9. Response curve of crop yield and water productivity (in economic terms) for applied water under micro-irrigation.



farmers might have incentive to go for micro irrigation for such crops. The water productivity gain automatically comes under such situations.

Changes in Input Use and Potential Impacts on Water Productivity

For a ‘linear response curve’ of yield to fertilizer dosage, the response curve for water productivity (Rs/m^3) may not be inverse exponential or inverse logarithmic; but ‘direct and linear’ as shown in the case of wheat in Hoshangabad for the year 2003 (Figure 9). Inverse relationships can occur only if the fertilizer dosage is accompanied by increased dosage of irrigation. But, with an increase in fertilizer dosage, the water productivity could actually rise, and then decline. This is because it would be possible to increase yields with an increase in fertilizer dosage, without much change in irrigation dosage up to a certain point. But, beyond a point, increased use of fertilizer dosage would require greater dosage of irrigation for increasing the nutrient absorption capacity of the plants, which reduces water productivity. Here adjusting the fertilizer dosage to optimal levels is crucial.

Through this, for the same dosage of irrigation water, crop yield can be enhanced to an extent with optimal dosage of fertilizers. This means that the physical productivity (kg/m^3) of water, apart from returns from land, could be enhanced through manipulation of fertilizer use.[6] This might increase water productivity in economic terms as well as, as seen in the earlier section. Such situation can be encountered in the central India best covering most parts of Narmada, Tapi, Mahi and Krishna basins, where fertilizer use in agriculture is one of the lowest.

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[6] But, primary data collected from farmers in Narmada Basin show that with increase in irrigation dosage, there is proportional increase in the dosage of fertilizers in most situations. Hence, the effect of fertilizer on crop yield and water productivity cannot be assessed through multiple regression model estimation procedures.

If fertilizer dosage is in a regime where the yield does not respond positively, then simple reduction in dosage would result in saving of input costs, thereby increasing water productivity in rupee terms. Such situations are possible in Punjab and Haryana where application of nitrogenous fertilizer is excessively high.

Potential Impacts of Improving Quality of Irrigation and Water Allocation

The analysis of Punjab and North Gujarat clearly show that improvement in quality of irrigation would significantly impact on yield (as shown in the case of Punjab) and water productivity (as shown in case of North Gujarat). Here, quality of irrigation includes adequacy and reliability (based on Kumar 2005). With greater reliability and adequacy of irrigation water deliveries, farmers would be able to adopt good agronomic practices and adjust nutrient use. With increasing uncertainty of water, farmers hesitate to apply adequate quantities of fertilizers, thereby compromising on the yield.

In case of farmers who are mainly using canal water for irrigation, it is quite common that the depth of each application is much higher than the optimum dosage decided by the field capacity as compared with those using well water. This leads to heavy percolation losses and reduces the efficiency of storage of water in the soil profile. It leads to excessive residual moisture after harvesting as well, which gets depleted in soil evaporation. Greater dosages may also increase the changes of fertilizer leaching, which leads to reduced nutrient use efficiency. Improving the quality of irrigation in such situation would help farmers optimize the irrigation dosages in each watering and give adequate number of waterings without changing the volume. This would not only increase the yield, but also reduce the wastage in irrigation, thereby enhancing water productivity of not only applied water, but also depleted water.

Allocating Water across Regions and Productivity Gains at the Basin Level

Spatial analyses of crop water productivity in Narmada Basin showed that water productivity of irrigated crops varies significantly across regions with changing agro-climate. The northern hills region of Chhattisgarh has moist sub-humid to dry-sub-humid climate. The four regions, viz., Kymore Plateau and Satpura Hills, Vindhya Plateau, Satpura Plateau and Central Narmada Valley (CNV) have ‘dry sub-humid’ climate. The regions, viz., Malwal Plateau, and Nimar Plain have semi-arid climatic conditions. The district of Jhabua, which falls in the region, named ‘Jhabua Hills’, is ‘semi-arid’[7].

While water productivity variations between two regions for the same crop can also be attributed to differential dosage of fertilizers, differential transpiration ratio and seed varieties, it is assumed here that variations in the same across regions are not significant.

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[7] Kumar and Singh 2006 for detailed description of average annual rainfall and reference evapotranspiration in all the nine agro-climatic regions falling in Narmada Basin.

The physical productivity figures are far below the normal figures for wheat in many regions. It was found to be the highest in the northern hill region of Mandla (Rs.1.8 kg/m^3), and the lowest in Jabalpur (0.47 kg/m^3) during a normal year. This difference could be attributed to the difference in agro-climate across regions, which reduces the denominator of water productivity, if we consider the fact that there are no major variations in yield levels between these regions. The variations are larger if one compares water productivity in Punjab. There, farmers obtain a return of 2.33 kg/m^3, irrespective of the aridity which increases irrigation water demand. This may be due to the high yield the farmers secure, with efficient use of water and fertilizers, and with the help of favorable agro-climate for growing winter wheat. The question, therefore, is whether the natural advantage which certain crops enjoy in certain regions in terms of higher water productivity by virtue of the agro-climate can be made use of, without compromising on farmers' need and priorities. This means, earmarking certain crops only in those regions where they have relative advantage in terms of getting high water productivity—both physical productivity and productivity in economic terms.

Potential for Improving Irrigated Water Productivity in India

Possible Crops and Areas for Increasing Irrigated Water Productivity

Regions which receive intensive canal irrigation are regions that should get priority in water productivity improvements because of 1) the water-intensive crops grown in these regions; 2) 'poor water delivery control'; and, 3) poor quality of irrigation. But, the regions should be such that irrigation water management practices comprising water delivery control and improvement in quality of irrigation result in reduction in non-beneficial evaporation. Therefore, semi-arid and arid regions with low water table conditions are ideal for this.

It is a general notion that water productivity is generally high in regions such as Punjab and Haryana, which receive extensive and intensive canal irrigation. This is based on high yield levels obtained for wheat and paddy in these regions. These regions are also known for intensive cropping of wheat and paddy. Our analysis for Punjab suggests that there is ample scope for improving yield in wheat and paddy through improving the quality of irrigation in terms of adequacy and reliability. In Punjab, such improvement of canal water supplies would lead to greater yield for wheat and paddy, apart from reducing non-beneficial depletion and improving water productivity. Hence, Irrigation Department should have incentive to go for improving both adequacy and reliability (quality) of irrigation water, and water delivery control. Since the area that can be irrigated cannot be expanded, it would lead to reduction in groundwater draft as well.

Groundwater irrigated areas, where a substantial area is still left uncultivated due to water scarcity, should receive attention for water productivity enhancements. The reason is it makes economic sense for the farmers as they can expand the area under irrigation and increase aggregate returns. The priority areas would be hard rock areas of peninsular, central and western India. A wide variety of crops are being grown in these regions such as cotton, castor, groundnut, mustard, banana, sugarcane, potato, and cereals such as paddy, *bajra* and sorghum. Among these, the water-intensive ones that are grown in large areas are paddy, cotton, sugarcane, banana, cotton, castor, groundnut, and potato. In crops such as paddy, water productivity enhancement has to come through ‘water control’[8] and ‘improving the quality of irrigation’. Wheat would be another crop which should receive attention in western Gujarat, Maharashtra and Rajasthan, and Central India. Such enhancement would come mainly from achieving ‘water control’.

In case of crops such as cotton, groundnut, potato, castor, banana and sugarcane, it can also come from the use of micro-irrigation devices, especially in sandy soils as it is very difficult to maintain high distribution uniformity in water application with traditional methods of irrigation such as level borders and furrows. Large-scale adoption of drip irrigation for banana and sugarcane in Maharashtra and for potato, groundnut, cotton and castor in North Gujarat bears testimony to this. Some recent analysis by Narayanamoorthy 2004 and Kumar et al. 2004 justify farmer investment on drip irrigation for banana and sugarcane. If it is so, enhancement in water productivity through micro-irrigation devices would be much higher than that through water delivery control.

Potential Improvements in Water Productivity at the Basin level

We have seen that the levels of water productivity achieved by most farmers in the sample from the three basins, viz., Indus, Ganges and Narmada, are much less than the maximum potential. We have also seen that there is some scope for raising the productivity of applied water in India for several crops through ‘water delivery control’”. But, under this approach, the productivity improvement comes from reduction in yield, resulting from reduction in consumptive use of water. The gain in applied water productivity results in the same extent of gain in productivity of depleted water only in semi-arid and arid regions where the depth to groundwater table is large.[9] and where non-beneficial evaporation from fallow is high. Hence, only in such regions where a significant portion of the applied water is depleted, there would be basin level productivity gains through water delivery control.[10] But, for farmers to go for water delivery control measures, they must have extra land to maintain the farm returns.

Though micro-irrigation would raise crop water productivity both in physical and economic terms without reducing yield (as illustrated by Figure 13), the impact of micro-irrigation again would be significant in arid and semi-arid areas, and for row crops. This is because in the case of row crops evaporation component of consumptive use of water by crop (ET) is quite large, especially under aridity. Again, the area under row crops is very small in the sub-humid and humid areas and water abundant areas.

The peninsular India and western India have substantial area under crops that are conducive to micro-irrigation technologies. Adoption of MI systems would lead to basin level

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[8] We refer to only water delivery control and possibility of water control through micro-irrigation is ruled out.

[9] Deep groundwater table and aridity means that the return flows from applied water are not significant; and evaporation of residual soil moisture from fallow is very high.

[10] In sub-humid and humid regions with shallow water-table, basin level water productivity gain would be very much lower.

water productivity improvements. Uttar Pradesh accounts for nearly 2 5% of the area that can be potentially brought under WSTs from 16 major states of India. But, the likely rate of adoption of WSTs in this state is going to be poor due to rural infrastructure, particularly rural electrification; relative water abundance; shallow groundwater in most areas; and very low size of operational holdings of farmers. Even if this region adopts WSTs on a large-scale, it may result not in reduction in depleted water, but a little difference in crop yields, with the resultant increase in basin level water productivity being meager. Western part of Mahanadi is another area that would be conducive to WSTs.

If we keep these considerations, the basins that are conducive to measures for improvement in water productivity through water control (comprising 'water delivery control' and 'micro-irrigation') are 1) all east-flowing rivers of peninsular India; 2) west-flowing basins north of Tapi in Gujarat and Rajasthan; Mahanadi; some parts of Indus Basin covering south-western Punjab; and west- flowing rivers of South India. The basins that are not conducive to water control measures are Ganga, Brahmaputra and Meghna. But, there are areas such as Bihar, eastern UP and Assam, where the crop yields are currently low. Increase in use of nitrogenous fertilizers and high-yielding varieties would help enhance the crop yields significantly. With no changes in the consumptive use of water, this could create major changes in water demand drivers. Due to economic scarcity of water,[11] farmers in Bihar would have incentive to enhance the return per unit of pumped water.

There are many regions in India where water productivity is not a consideration for individual farmers, though the economy would benefit a lot by reducing the amount of water depleted and the energy used for growing crops. These are groundwater irrigated areas where there are no physical or economic constraints on the amount of water farmers can pump. In these areas, farmers want to maximize the returns per unit of land as their entire land is already irrigated. Such areas include parts of Indus in central Punjab, Haryana and UP. In these areas, water availability is not a constraint in maximizing farm returns, but land availability is. In such areas, water productivity improvement measures should help raise income returns from every unit of land irrigated. Hence, the only option to enhance water productivity available is water delivery control, and can be used in situations where excessive irrigation leads to yield losses.

Implications of Water Productivity Change on Water Demand Drivers

Enhancement in applied water productivity through 'micro irrigation', would have significant implications for water demand in agriculture per unit area of cultivated land in semi-arid and arid area, if the depth to groundwater table is large or the aquifers are saline. But, it will have least effect in sub-humid and humid areas. But, in semi-arid and arid areas, the farmers would use the saved water to expand the area under irrigation to maximize their aggregate returns in the presence of sufficient uncultivated land, and as a result the aggregate demand for water may not change.

On the other hand, reduction in non-beneficial depletion of water through 'water delivery control' would nevertheless be high in arid and semi-arid areas with deep groundwater tables. But, here again, farmers would expand the area under irrigation, as their returns per unit area would decline. The result would be no reduction in aggregate demand for water. Exceptions

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[11] Many marginal and small farmers pay very high charges for pump rental services for irrigating crops.

would be those in which farmers water their crops in excess of the crop requirement leading to yield losses. On the other hand, in sub-humid and humid and cold climates with shallow groundwater conditions, the reduction in non-beneficial depletion would be much less. This is because, with increase in dosage of water under traditional methods of irrigation, the amount of water which is available as return flows as a percentage of the total water applied would be higher. Examples are eastern region of India where groundwater table is very shallow. But, in such areas, it is very unlikely that farmers adopt measures which are at the cost of yield reduction. Hence, no reduction in aggregate demand for water is expected in such basins also.

At the same time, in sub-humid and humid areas having plenty of water—either surface or groundwater—the enhancement in applied water productivity through manipulation of fertilizer and crop technology inputs can reduce the irrigation water supply requirement per unit area if the yields are just to be maintained at the current level. Such outcomes are extremely valuable in view of the fact that there are millions of farmers in this area, who are still dependent on purchased water for irrigating their crops. But, in practice, with the adoption of high yielding varieties and increased fertilizer dosage, farmers would proportionally increase the dosage of irrigation. Therefore, the aggregate demand for irrigation would go up even if one does not anticipate any change in area under irrigation.

Conclusion

Overall, the empirical evidence provided from three important river basins shows that: a) there are major variations in physical productivity of water and water productivity in economic terms across farmers in the same area; b) the same crop grown in different regions has remarkably different levels of physical productivity of water and water productivity in economic terms; and, c) the same crop has differential water productivity with different qualities of irrigation water applied. The variation in water productivity (Rs/m^3) for the same across farmers in the same location was explained by the following facts: 1) most farmers are applying water within a regime where the yield response to both irrigation and fertilizer dosage is positive; and 2) water productivity response to irrigation is negative. Nevertheless, in certain situations, the water application regime of farmers corresponds to a regime where both yield and water productivity responses to irrigation are either positive or negative. In sum, the water productivity realized by farmers is much less than the maximum potential.

Following are the four major ways of enhancing crop water productivity: a) water control comprising 'control over water delivery' and micro-irrigation; b) improving quality (adequacy and reliability) of irrigation; c) manipulating other inputs, mainly fertilizers; and d) earmarking certain crops only for those regions where they have relative advantage in terms of getting high water productivity. But, in most situations, trade-offs exist between enhancing water productivity in economic terms and crop yields through water delivery control. Due to this trade off, farmers would have incentive to pursue water productivity improvement measures only if extra land is available, so as to divert the saved water to expand the area under irrigation and sustain the aggregate returns.

Field level water productivity improvements through water delivery control and use of micro irrigation, together called 'water control', would result in basin-level water productivity improvement in basins falling in semi-arid and arid regions of India with deep water table conditions. But, this would not result in water-saving at the basin level. Situations where both basin-level water productivity enhancement and real aggregate level water saving, occur due to water control are quite rare.

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Drip and Sprinkler Irrigation in India: Benefits, Potential and Future Directions

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Background

Water is becoming increasingly scarce worldwide and more than one-third of the world population would face absolute water scarcity by the year 2025 (Seckler et al. 1998; Seckler et al. 1999; Rosegrant et al. 2002). The worst affected areas would be the semi-arid regions of Asia, the Middle-East and sub-Saharan Africa, all of which are already having a heavy concentration of population living below poverty line. The situation in India is also critical, where absolute water scarcity is already affecting a substantial part of the population and this proportion is increasing rapidly (Amarasinghe et al. 2005, 2007).

Much of the water scarcity in India is due to spatial variation in demand and supply of water. Irrigation, is the largest water consuming sector, accounting for more than 80 % of the total withdrawals. Yet, irrigation so far has covered only about 40 % of the gross cropped area, even though India has the largest irrigated area in the world. Given the increasing scarcity and also nonagricultural water demand, demand management is receiving special attention. In India, although a number of demand management strategies in the irrigation sector have been introduced with a view to increasing the water use efficiency (Vaidyanathan 1998; Dhawan 2002), however the net impact of these strategies in increasing the water use efficiency so far has not been very impressive. One of the demand management strategies introduced relatively recently to manage water consumption in Indian agriculture is micro-irrigation (MI). Unlike flood method of irrigation (FMI), micro-irrigation supplies water at the required interval and in desired quantity at the location where water is demanded using a pipe network, emitters and nozzles. Therefore, MI in principle should result in low conveyance and distribution losses and lead to higher water use efficiency.

Among advanced micro-irrigation (MI) techniques, drip and sprinklers are gaining special attention. Drip irrigation (DIM) and sprinkler irrigation (SIM) methods have distinct characteristics in parameters such as flow rate, pressure requirement, wetted area and mobility (Kulkarni 2005), but they have the potential of significantly increasing water use efficiency. While DIM supplies water directly to the root zone through a network of pipes and emitters, SIM sprinkles water, similar to rainfall, into the air through nozzles which subsequently breaks into small water drops and fall on the field surface. DIM has little or no water losses through conveyance (INCID 1994; Narayanamoorthy 1996, 1997; Dhawan 2002), and the on-farm irrigation efficiency of a properly designed and managed drip irrigation system can be as high as 90 %, compared with 35 to 40 % efficiency in surface method of irrigation (INCID 1994). However, SIM has relatively less water saving (up to 70 % efficiency), since it supplies water over the entire field of the crop (INCID 1998; Kulkarni 2005).

Besides higher water use efficiency, MI has other economic and social benefits too. Research station experiments show MI increases productivity by 20 to 90 % for different crops (INCID 1994, 1998); reduces weeds, soil erosion; cost of cultivation, especially in labor-intensive operations; energy use (electricity) for operating irrigation wells due to reduced water consumption (Narayanamoorthy 1996 and 2001).

Studies show MI has an enormous potential in India, where DIM and SIM can cover about 80 crops (overview of MI development in INCID 1994 and 1998). DIM is highly suitable for wide spaced crops, but it is also being used for cultivating oilseeds, pulses, cotton and even for wheat crop. SIM is mostly suitable for closely grown crops like cereals, pulses, wheat, sugarcane, groundnut, cotton, vegetables, fruits, flowers, spices and condiments. An experimental study suggests that sprinklers can also be used successfully for cultivating paddy crop (Kundu et al. 1998). Unlike conventional method, MI also has the advantage of irrigating undulating terrain, rolling topography, hilly areas, barren land and areas which have shallow soils (Sivanappan 1994). In spite of many advantages, MI coverage in India, except in a few states, is not appreciable. High capital investments (ranging from Rs. 20,000 to 55,000 per hectare depending upon the nature of crops and the material to be used), little or no cost of surface irrigation supplies; free electricity for pumping groundwater have been the important impediments for faster adoption of MI techniques. However, an increase in the DIM adoption has taken place since the 1980s, mainly as a result of various promotional programmes introduced by the Central and State Governments (Narayanamoorthy 2005).

In spite of the enormous potential for different crops, not many studies seem to have been undertaken to analyse the potential and prospects of drip and sprinkler irrigation for different states in India. This paper, using the available secondary information, attempts to fill this void. The specific objectives of the study are: (a) to assess the past trends in drip and sprinkler irrigated area across states; (b) to estimate the potential area for drip and sprinkler irrigation in different states; and (c) to suggest policies for increasing the adoption of WSTs in the future.

Trends in Area under Drip and Sprinkler Irrigation[1]

DIM and SIM adoption in India are not the same across crops and regions. While DIM is largely found in states like Maharashtra, Andhra Pradesh and Tamil Nadu, SIM is largely adopted in states like Haryana, Rajasthan and Madhya Pradesh (INCID 1994, 1998; GOI 2004).

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[1] One of the serious constraints faced by the researchers working on micro-irrigation is the data availability. Though most of the area currently cultivated under micro-irrigation is established through various government sponsored schemes, coverage of area under MI by states and by crops are seldom published by any single agency. This does not allow the researchers to study the trends and determinants of micro-irrigation across states in a detailed manner. This section is written with great data constraint.

Crops that are cultivated with these two methods of irrigation are also not the same. As already mentioned, wide spaced crops are highly suited for DIM, whereas close spaced crops are suitable for SIM. Therefore, we asses the DIM and SIM trends separately.

The development of DIM was very slow initially, but its spread increased significantly since 1990s due to various promotional schemes introduced by the Government of India and states like Maharashtra. DIM area increased from a mere 1,500 ha in 1985 to 70,589 ha in 1991-92, and to 2,46,000 ha in 1997-98 (INCID 1994; AFC 1998). As of 2003, the DIM area has increased to about 450 thousand hectares, of which 78 % of the area is under Government of India Schemes. However, as mentioned in the Report of the Task Force on Micro-irrigation, a large number of institutions, commercial organisations, universities, large public/private sector companies, NGOs, etc., have taken up drip irrigation in the country for their farms/crops, which are estimated to be of about 1, 00,000 ha in area. This area has not been reflected in the estimate made by the government departments. Therefore, the total DIM area in the country could be as high as 500,000 hectares as of March 2003 (GOI 2004).

Drip irrigated area has increased substantially in the 1990s across almost all the Indian states (Table 1). During all the three time periods studied, Maharashtra State alone accounted for nearly 50 % of India's total drip irrigated area, followed by Karnataka, Tamil Nadu and Andhra Pradesh. However, DIM area still constitutes a very small proportion of the total irrigated area in all the states in India - only 0.48 % of the gross irrigated area and about 1.09 % of the gross groundwater irrigated area in 2000-01.

Although DIM technology can be applied to over 80 crops in India, its use so far has been limited to only a few crops. As of 1997-98, coconut, grapes, banana, citrus, mango and

Table 1. State-wise area under drip method of irrigation.

State	Area ('000 ha)			Percent of total area		
	1991-92	1997-98	2000-01	1991-92	1997-98	2000-01
Maharashtra	32.9	122.9[a]	160.3	44.64	50.00	53.16
Karnataka	11.4	40.8[b]	66.3	16.17	16.58	18.03
Tamil Nadu	5.4	34.1	55.9	7.59	13.86	15.20
Andhra Pradesh	11.6	26.3	36.3	16.41	10.70	9.88
Gujarat	3.6	7.0	7.6	5.05	2.85	2.07
Kerala	3.1	4.9	5.5	4.30	1.98	1.50
Orissa	0.1	2.7	1.9	0.06	1.10	0.52
Haryana	0.1	1.9	2.1	0.17	0.77	0.55
Rajasthan	0.3	1.6	6.0	0.43	0.65	1.63
Uttar Pradesh	10.1	1.5	2.5	0.16	0.61	0.68
Punjab	0.1	1.1	1.8	0.03	0.45	0.49
Other States	2.2	1.1	5.4	3.00	0.47	1.47
Total	70.6	246.1	367.7	100.00	100.00	100.00

Source: AFC 1998 and GOI 2004

Note: a- includes state subsidy scheme area of 58498 ha; b- includes area under central and state schemes for development of oil palm and sugarcane.

pomegranate together accounted for 67 % of the total DIM area. Maharashtra, Andhra Pradesh, Tamil Nadu and Karnataka account for a major share of the area of the above crops. For example, Maharashtra alone accounted for 93 % of the 26,460 ha of the banana area under drip irrigation. It clearly suggests that despite having severe water scarcity in different regions, the adoption of the drip method of irrigation is only concentrated in a few states.

Sprinkler irrigation method is relatively old for Indian farmers as compared with drip irrigation method. Sprinkler was introduced in India during the mid-1950s for plantation crops like coffee and tea. Over the years, SIM spread into large areas in states like Haryana, Rajasthan, MP, Maharashtra and Karnataka. Unlike DIM, detailed and accurate statistics are lacking for sprinkler irrigation. The gross area under sprinkler irrigation has increased from 0.23 mha in 1985 to 0.67 mha in 1998. According to the National Committee on Plasticulture Applications in Horticulture (NCPAH), the total SIM area is estimated to have increased to 1.63 mha. This is almost 300 % higher than the present area under drip method of irrigation. SIM adoption across states also vary, it is mainly concentrated in the central and the northern part of the country (Table 2). In 2004-05, Haryana, Rajasthan, West Bengal and Maharashtra together accounted for 70 % of India's total SIM area.

Table 2. State-wise area under sprinkler irrigation: 1997-98 and 2004-05.

States	Area ('000 ha)		Percent to total area	
	1997-98	2004-05*	1997-98	2004-05*
1. Madhya Pradesh	149.9	85.0	22.78	5.20
2. West Bengal	120.0	135.0	18.23	8.26
3. Assam	90.0	125.0	13.67	7.65
4. Haryana	83.6	490.0	12.70	29.97
5. Rajasthan	47.8	425.0	7.27	25.99
6. Karnataka	41.9	125.0	6.36	7.65
7. Maharashtra	33.1	110.0	5.03	6.73
8. Tamil Nadu	32.1	10.0	4.88	0.61
9. Gujarat	27.7	11.0	4.21	0.67
10. Andhra Pradesh	17.1	55.0	2.60	3.36
11. Uttar Pradesh	7.4	10.0	1.12	0.61
12. Kerala	5.8	8.0	0.88	0.49
13. Bihar	0.2	0.5	0.02	0.03
14. Himachal Pradesh	0.1	0.3	0.01	0.02
15. Jammu & Kashmir	0.03	0.2	0.00	0.01
16. Orissa	0.4	12.0	0.06	0.73
17. Punjab	0.2	10.0	0.03	0.61
18. Others	0.5	23.1	0.08	1.41
Total	658.5	1,634.9	100.00	100.00

Source: INCID 1998 and NCPAH 2005

Note: * - Figures are approximate, estimated based on the graph provided by NCPAH

The reasons for the large-scale adoption of sprinkler irrigation vary from state to state. Though MP receives medium rainfall, it is irregular and the summer has long dry spells. This encourages MP farmers to adopt sprinkler irrigation for crops like soybean in various parts of the state. In Haryana, the soil condition, topography and the climates that are prevailing in the south western part of the state, especially in districts of Bhiwani, Mahindergarh, Rothak, Sirsa and Hisar, have prompted the adoption of sprinkler irrigation. Similarly, favorable cropping patterns for MI and water scarcity during the summer season are the main reasons for the relatively higher adoption of sprinkler irrigation in Rajasthan (INCID 1998).

Although the SIM reported area is much higher than that under drip irrigation, no reliable data is available on the composition of crops that are cultivated presently using this method of irrigation. The INCID 1998 report presents a whole lot of information about the sprinkler method, but does not provide where and what crops are cultivated under this method. In fact, reliable and time series data on micro-irrigation is seldom available even for research purpose. Agencies involved in promoting MI should make all efforts to publish data on the development of micro-irrigation in terms of crop composition, area by state, districts and different size classes, area by state promoted schemes and other schemes. This would help one to analyse the underlying factors and suggest possible ways and means to increase the adoption of such water saving technologies.

Potential Areas for Drip and Sprinkler Irrigation in India

In spite of the large capital investments, MI seems to generate better returns for farmers, even without government subsidies (Table 3). Although micro-irrigation has proved to be a very useful method for efficient use of irrigation water, not many studies have attempted to estimate the total potential area for drip and sprinkler method of irrigation for different states in India. Therefore, in this section, we try to estimate the total potential area for drip and sprinkler irrigation methods across different states in India.

Before presenting our own estimates, we first discuss the estimates of potential DIM and SIM l area on the basis of available literature. Two estimates are available as the potential DIM area - 18.2 Mha by NCPA 1990, and 27.0 Mha by the Task Force on Micro-Irrigation (TFMI) (GOI 2004). The potential SIM area estimates vary, from 42.5 Mha of INCID 1998 to 69.5 Mha of TFMI, (Table 4). What could be the possible reasons for such wide variation in these estimates? It appears that there are some methodological problems with the available estimates. It is not clear whether the estimates include irrigated cropped area alone or both irrigated plus un-irrigated cropped area. It also appears that the TFMI estimate includes both irrigated and un-irrigated cropped areas (example cotton area). Since water sources are needed to use micro-irrigation, one should not include un-irrigated cropped area while estimating potential area for drip and sprinkler irrigation.[2] Moreover, both the estimates have not provided

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[2] Potential area for MI can be estimated in various ways using different assumptions. If one wants to include un-irrigated crops that are suitable for MI for estimation, it is essential to specify under what condition this would be possible. In any case un-irrigated crop area may not be immediately brought under the method of MI.

Table 3. Field survey results of drip irrigation: banana, grapes and sugarcane.

Particulars	Crop's name	Method of irrigation		Benefit over FIM	
		DIM	FIM	In percent	In value
Water consumption (HP/hours/ha)	Banana	7,884.70	11,130.30	29.20	3245.60
	Grapes	3,310.40	5,278.40	37.30	1968.00
	Sugarcane	1,767.00	3,179.98	44.43	1412.98
Productivity (quintal/ha)	Banana	679.50	526.35	29.10	153.20
	Grapes	243.25	204.29	19.10	38.96
	Sugarcane	1,383.60	1,124.40	23.05	259.20
Electricity consumption (Kwh/ha)	Banana	5,913.33	8,347.75	29.16	2,434.42
	Grapes	2,482.77	3,958.78	37.28	1,476.01
	Sugarcane	1,325.25	2,384.99	44.43	1,059.74
Water use efficiency (HP hours/quintal)	Banana	11.60	21.10	45.10	9.50
	Grapes	13.60	25.80	47.30	12.20
	Sugarcane	1.28	2.83	5.48	1.55
Cost of cultivation (Rs/ha)	Banana	51,437	52,740	2.50	1303
	Grapes	1,34,506	1,47,915	9.10	13,409
	Sugarcane	41,993	48,540	13.49	6,547
Gross income (Rs/ha)	Banana	1,34,044	102935	30.22	31,109
	Grapes	2,47,817	211038	17.40	36,779
	Sugarcane	106366	85,488	24.00	20,878
Capital cost of drip-set (Rs/ha)(without subsidy)	Banana	33,595	—	—	—
	Grapes	32,721			
	Sugarcane	52,811	—	—	—
Net present worth (Rs/ha)*(without subsidy)	Banana	2,41,753	—	—	—
	Grapes	5,40,240			
	Sugarcane	169896	—	—	—
Benefit-cost ratio* (without subsidy)	Banana	2.288	—	—	—
	Sugarcane	1.909			
	Grapes	1.767	—	—	—

Source: Computed using Narayanamoorthy 1996, 1997 and 2001

Notes: Banana and grapes data relate to the year 1993-94 and sugarcane data relate to the year 1998-99;
* - 15 % of discount rate is considered for computing benefit cost ratio.

state-wise potential, which reflect the true variation of land use and cropping pattern. Keeping in view the limitations of the existing estimates, we make a fresh attempt to estimate the potential area for drip and sprinkler irrigation separately covering all the major states.

Various crops that are highly suitable for drip method of irrigation are extensively cultivated in different parts of India. Micro-irrigation is not only suitable for those areas that are presently under cultivation, but it can also be operated efficiently in undulating terrain,

Table 4. Available estimate on potential area for drip and sprinkler irrigation in India.

(Area in mha)

Crop	INCID(sprinkler)	TFMI (drip)	TFMI (sprinkler)
Cereals	27.6	—	27.6
Pulses	4.2	—	7.6
Oilseeds	11.1	3.8	4.9
Cotton	2.6	7.0	8.8
Vegetables	2.5[a]	3.6	6.0
Spice and condiments	1.2	1.4	2.4
Flowers, medicinal and aromatic plants	—	—	1.0
Sugarcane	3.3	4.3	4.3
Fruits	—	3.9	3.9
Coconut, plantation crops, oil palm	—	3.0	3.0
Total	42.5	27.0	69.5

Sources: INCID 1998 and GOI 2004

Note: a – includes fruits and vegetables.

rolling topography, hilly areas, barren lands and areas which have shallow soils (Sivanappan 1994). Since most of the potential areas are not under cultivation presently, for the purpose of the analysis, we broadly divide the total potential into two categories as 'distant potential' and 'core potential'. 'Distant potential' refers to all those areas that are suitable for drip method of irrigation, but may not be under cultivation presently. Lands (area) that are falling under the categories of barren and unculturable lands, culturable wastelands and fallow lands can be treated as 'distant potential'. In India, as per the land utilization data of 2000-01, about 56.28 million hectares of land is available under these categories. Unlike FIM, land-levelling and ploughing are not necessary for cultivating crops (especially horticultural crops) under DIM. Therefore, without incurring heavy expenditures on land reclamation activities, these areas could be brought under DIM cultivation in a phased manner.

However, since an irrigation source is essential for adopting micro-irrigation, we have excluded all those areas that are suitable for drip irrigation, but not currently under irrigation. We focus our estimate to the area already under irrigation. That is, only those suitable crops that are currently cultivated under irrigation is treated as potential area for drip irrigation. The important crops that are suitable for DIM are pulses, groundnut and other oilseed crops, sugarcane, fruits, vegetables, flowers, condiments and spices, cotton, etc. The state-wise area under these crops (Table 5) shows that the total potential area for drip irrigation is about 21 mha for the country as a whole, which is almost 6 million hectares less than the TFMI estimate. Of this potential, area for oilseed crops alone accounts for 27.7 %, followed by sugarcane, fruits and vegetables. As expected the potential area available from each state varies considerably, because of varied cropping pattern and availability of irrigation facilities. Among the states, Uttar Pradesh has more potential followed by Rajasthan, Gujarat, Maharashtra, Punjab and Madhya Pradesh. In fact, Uttar Pradesh, Rajasthan and Punjab together account for about 50 % of India's total potential area for drip method of irrigation.

Table 5. State-wise potential for drip method of irrigation: 2000-01.

(Area in '000 ha)

States	Pulses	S.cane	C &S	F & V	Oil seeds	Cotton	Others	Total
1. AP	21	360	233	328	423	192	127	1,684 (8.02)
2. Assam	-	-	-	-	2	-	0	2 (0.01)
3. Bihar	19	33	8	286	55	-	13.7	415 (1.97)
4. Gujarat	68	255	173	295	727	631	116	2,265 (10.78)
5. Haryana	59	140	5	58	350	554	0	1,166 (5.55)
6. HP	6	1	2	14	3	@	0	26 (0.12)
7. J & K	4	@	1	20	55	@	1	81 (0.39)
8. Karnataka	80	417	160	200	500	73	72	1,502 (7.15)
9. Kerala	-	3	36	29	166	-	0	234 (1.11)
10. MP	937	74	117	145	207	144	0	1,624 (7.73)
11. Maharashtra	267	595	135	599	232	131	6	1,965(9.35)
12. Orissa	64	31	50	210	53	-	4	412(1.96)
13. Punjab	49	116	4	137	116	721	9	1,152(5.48)
14. Rajasthan	382	13	410	89	1,311	496	1	2,702(12.86)
15. TN	60	315	73	276	553	65	8	1,350(6.43)
16. UP	624	1,844	30	743	719	5	13	3,978(18.93)
17. WB	-	8	-	-	326	-	0	334 (1.59)
INDIA	2,652 (12.62)	4,217 (20.07)	1,446 (6.88)	3,508 (16.07)	5,826 (27.73)	3,013 (14.34)	341 (1.65)	21,009 (100)

Sources: Computed using GOI 2003; www.agricoop.nic.in

Notes: S.cane- sugarcane; C&S – condiments & spices; F & V – fruits & vegetables; Figures in brackets are percentages to total; @ - below 500 hectares

The characteristics of sprinkler irrigation method are somewhat different from those of drip method of irrigation. While drip method of irrigation is highly suitable for wide spaced crops, sprinkler irrigation is mostly suitable for closely grown crops like cereals and millets, and also for horticultural crops. Experimental studies do suggest that SIM is suitable for even paddy crops. SIM also suits undulating terrain, rolling topography, hilly areas, barren lands and areas which have shallow soils (INCID 1998). But these areas are not under irrigation, so we exclude them too. The estimate presented in Table 6 shows that India's total potential for sprinkler irrigation would be about 50.2 mha. If we exclude the area under cereal crops from the estimate, the total potential would only be about 23.5 mha, which is almost equivalent to the potential area available for drip irrigation method. The total potential can go up to 74.2 mha, if paddy area is also included for estimation.

Similar to drip potential area, the potential area available for SIM also varies across the states, because of the differences in cropping pattern and irrigation availability. Our estimates show that UP state alone accounts for about 27.70 % of India's total potential, followed by

Table 6. State-wise potential for sprinkler irrigation: 2000-01.

(Area in ‘000 ha)

States	Cereals	Pulses	S.cane	C& S	F &V	Oil seeds	Cotton	Others	Total
1. AP	254	21	360	233	328	423	192	134	1,945 (3.87)
2. Assam	1	-	-	-	-	2	-	0	3 (0.01)
3 Bihar	3,417	19	33	8	286	55	-	13.7	3,832 (7.63)
4. Gujarat	697	68	255	173	295	727	631	312	3,158 (6.29)
5. Haryana	2,593	59	140	5	58	350	554	393	4,152 (8.27)
6. HP	97	6	1	2	14	3	@	5	128 (0.25)
7. J & K	118	4	@	1	20	55	@	31	229 (0.46)
8. Karnataka	677	80	417	160	200	500	73	77	2,184 (4.35)
9. Kerala	0	-	3	36	29	166	-	37	271 (0.54)
10. MP	2,364	937	74	117	145	207	144	121	4,109 (8.18)
11. Maharashtra	1,287	267	595	135	599	232	131	6	3,252 (6.48)
12. Orissa	37	64	31	50	210	53	-	4	449 (0.89)
13. Punjab	3,550	49	116	4	137	116	721	677	5,370 (10.69)
14. Rajasthan	2,801	382	13	410	89	1311	496	421	5,923 (11.79)
15. TN	130	60	315	73	276	553	65	27	1,499 (2.98)
16. UP	9,367	624	1,844	30	743	719	5	620	13,952 (27.78)
17. WB	339	-	8	-	-	326	-	0	673 (1.34)
India	26,703 (53.17)	2,652 (5.28)	4,217 (8.40)	1,446 (2.88)	3,508 (6.99)	5,826 (11.60)	3,013 (6.00)	2,856 (5.69)	50,221 (100.0)

Source: Same as in Table 5

Note: The crops mentioned in the table are identified as the suitable crops for SIM by the INCID 1998.

Rajasthan, Punjab, Haryana, MP and Bihar. The state level position can change completely, if we exclude the cereal crops from the estimate. For instance, in the case of UP state, the potential area would go down from 13.95 mha to 9.37 mha, if cereal area is excluded from the estimate. Similarly, the potential of Punjab would be only 1.82 mha, instead of 5.37 mha. We presume that the large-scale adoption of sprinkler irrigation may not take place immediately given the low canal water rates and electricity tariffs. Therefore, it is prudent to classify the potential into two as ‘soft’ and ‘hard’ potential so that policy decision can be made easily for achieving the target.

It is to be noted here that the potential area for drip and sprinkler method of irrigation is expected to change over time depending upon the land use pattern, crop pattern, irrigated area and the level of groundwater exploitation across states. The proactive policy of the state can also influence the adoption of WST significantly, as has been experienced in Maharashtra. Given the overexploitation of groundwater in different parts of the country and changes in cropping pattern, the estimated potential area for both drip and sprinkler method of irrigation might increase considerably in the future.

Conclusion and Policy Interventions

The estimate presented in the preceding section suggests that the potential for both drip and sprinkler irrigation is very large in different states of India. Micro-irrigation reduces the cost of cultivation, weed problems, soil erosion and increases water use efficiency as well as electricity use efficiency, besides helping reduce the overexploitation of groundwater. In spite of having many economic and other advantages, the growth of area under micro-irrigation has not so far been appreciable compared to the total potential. As of now, the area under drip irrigation has extended to only 2.13 % of its potential while in the case of sprinkler irrigation the corresponding proportion is 3.30 %. Additionally most of this development has been due to the support (subsidy) from state agency. Quite a few policy and technical reasons have been identified for the slow growth and the adoption of WSTs in India. Given the vast potential benefits of micro-irrigation and fast decline of irrigation water potential in the country, a number of technical and policy interventions are required to be introduced so as to increase the adoption of micro-irrigation in India. Some specific interventions needed are presented below:

1. Sprinkler irrigation has generally been promoted through subsidy schemes and not as an on-farm water and land management strategy. In certain states (for example, Maharashtra), under subsidy scheme, no consideration is given in respect of field size, shape, topography, type and the location of water source, seasonal fluctuations, type of soil and crops to be grown. The design aspect is ignored so as to reduce the cost of the system. According to Kulkarni 2005, “in most cases the subsidy sets do not match the site specific situations of an individual farmer. As a result, the sets do not operate satisfactorily” (p.5). This can discourage the farmers not to adopt sprinkler irrigation. Therefore, the subsidy scheme needs to be modified and must take in to consideration the design aspect of the system.

2. Both drip and sprinkler irrigation are driven through the state and central government sponsored subsidy schemes. In order to earn quick profit from the subsidy programs, many companies are marketing various sub-standard components in the market. Often the sub-standard components affect the working condition of the system which creates enormous doubt in the farmer’s mind about the functioning of the system. It is to be ensured that only good quality components having the certification of Bureau of Indian Standards (BIS/ISO) are supplied to the farmers. There is also a need to establish a Central Testing Facility (CTF) to deal comprehensively with the design, development and testing of all equipment, devices and machines used in sprinkler and micro-systems using state-of-the-art technology (Kulkarni 2005; GOI 2004).

3. There has been a significant development in sprinkler technology all over the world. Several variations of sprinkler irrigation system, with improved design and components are available in those countries, where it is popularly used. Efforts should be made to manufacture such improved sprinkler systems through joint ventures, with the condition that the imported components and technology would be transferred to indigenous manufacture within a period of 2 years. This would help reducing the cost of the system and increasing the adoption of micro-irrigation at a large scale. As suggested by TFMI, at least 1 % of the outlay on micro-irrigation needs to be earmarked for micro-irrigation research.

4. One of the major reasons for the slow growth of micro-irrigation in India is the high initial investment. In spite of the availability of subsidy from state agencies, the majority of the farmers are reluctant to invest in micro-irrigation system even in horticulture crops, which is highly suitable for drip irrigation. Therefore, as suggested by TFMI, there is a need to look into the technological options, of which crop geometry modification is the most important one. Instead of adopting traditional spacing, adoption of paired row planting has been found to reduce the cost of the system by 40 % in many crops including tomato, brinjal, okra, etc. Therefore, micro-irrigation system should be tailor made, i.e., planned and designed based on location specific parameters. Standard procedure provided under subsidy scheme may not always help to reduce the cost of the system.

5. It is understood from the field studies that capital cost required to install drip irrigation is relatively high. Because of this reason, considerable percentage of farmers have expressed that they are unable to adopt this technology for low- value crops. If drip system is made available at a low cost, area under drip irrigation can be increased at a faster rate. Therefore, measures need to be taken to reduce the fixed cost of drip irrigation by promoting research and development activities. By recognizing drip industry as an infrastructure industry as well as announcing tax holiday for specific time periods to all those drip set industries which produce genuine drip materials, the competition can be increased to ultimately bring down the cost of the system. Some companies have come out with low-cost drip irrigation systems, which can be adopted even by the farmers having less than one acre of land. Studies need to be carried out to find out the feasibility of low- cost drip materials including its environment feasibility using field level data.

6. The centrally sponsored scheme of drip irrigation does not provide a subsidy for the sugarcane crop. The logic behind this is not clearly known. Since it is an important and also a heavy water-consuming crop, this restriction should be removed to increase the drip irrigated area at a faster rate. This would also ultimately help to reduce the water crisis faced by various states to some extent.

7. The rate of subsidy provided through government schemes is fixed uniformly for both water-intensive as well as less water-intensive crops. This needs to be restructured. Special subsidy program may be introduced for water-intensive crops like sugarcane, banana, vegetables, etc. Differential subsidy rates can be fixed based on the types of crops and the rate of consumption of water. Uniform level of subsidy schemes currently followed for water-scarce and water-abundant areas need to be changed and higher subsidy should be provided for those regions where the scarcity of water is acute and exploitation of groundwater is very high as well.

8. Sugar industries always try to increase the area under sugarcane to increase their capacity utilization in almost all the states in India. They are least bothered about the method of sugarcane cultivation. Since sugar industries have close contact with sugarcane cultivators, some kind of target may be fixed for each sugar industry to bring cultivation of sugarcane under DIM. Apart from the saving of water, this would also help achieve cultivation of sugarcane in a sustainable manner. Despite irrigation water shortage in many states, not only does the area under sugarcane continue to

grow at a relatively faster rate, but it is cultivated predominantly under flood method of irrigation. This puts additional pressure on our limited water resources.

9. Drip set manufacturers should be asked to involve intensively in promoting micro-irrigation by organizing frequent demonstrations at farmers' fields. Since the use of micro-irrigation is still in the take-off stage in India, an active role of the manufacturers is essential in promoting drip irrigation as well as developing confidence among the farmers about the usefulness of this new technology. The micro-system manufacturers should be involved in providing advice on agronomic packages to the farmers so as to encourage the adoption of WSTs on a large scale.

10. For a speedy growth of micro-irrigation, a special package scheme can be introduced where priority can be given to providing bank loans for digging wells and electricity connection (pump-set) for those farmers who are ready to adopt micro-irrigation for cultivating any crop.

11. Groundwater is the only source of water being used for drip method of irrigation in India. Unlike other countries, water from surface sources (dams, reservoirs, etc.) is not used for drip method of irrigation. Since water use efficiency under surface sources is very low owing to heavy losses through conveyance and distribution, farmers should be encouraged to use water from surface sources for drip method of irrigation. This can be done by allocating a certain proportion of water from each irrigation projects only for the use of micro-irrigation.

12. One of the important reasons for the low spread of this technology even in the water-scarce area is the availability of highly subsidized canal water as well as electricity for irrigation pump sets. Appropriate pricing policies on these two inputs may also encourage the farmers to adopt this technology.

To conclude, the potential area for MI presented above is estimated based on the present cropping pattern and irrigation coverage of different states in India. One may not be able to argue that this potential area would be the same even after 10 or 20 years because of changes in the parameters that determine MI potential. The potential area available for MI is governed by factors such as cropping pattern, irrigation coverage, groundwater scarcity, price of canal water, price of electricity as well as its supply (in hours) for agriculture, technology development in MI, proactive policy (subsidy and other incentives) of the state and central governments. In case farmers shift the cropping pattern more in favour of horticultural crops because of their high profitability, the potential area for DIM might increase significantly in the future. Similarly, if the depletion in groundwater in different regions aggravates further, it might also encourage the farmers to shift the irrigation method from flood to MI methods. What will be the potential area for DIM and SIM if cropping pattern changes drastically in favor of high-value horticultural crops in another 10 years? Does the potential for MI change if one estimates it under different scenarios of groundwater depletion? Will the potential area for MI change if full cost pricing is introduced in canal water and electricity supplied for irrigation pump sets? One may be able to find some interesting results if comprehensive analysis is carried out covering the issues flagged here. In any case, the potential area for MI is not going to be static.

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Water Saving and Yield Enhancing Micro-irrigation Technologies: How Far Can They Contribute to Water Productivity in Indian Agriculture?

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Introduction

Demand management becomes the key to the overall strategy for managing scarce water resources (Molden et al. 2001). Since agriculture is the major competitive user of diverted water in India (GOI 1999), demand management in agriculture in water-scarce and water-stressed regions would be central to reducing the aggregate demand for water to match with the available future supplies, thereby reducing the extent of water stress that the country is likely to face (Kumar 2003a; Kumar 2003b). Improving water productivity in agriculture is important in the overall framework for managing agricultural water demand, thereby increasing the ability of agencies and other interested parties to transfer the water thus 'saved' to economically more efficient or other high priority domestic and industrial use sectors (Barker et al. 2003; Kijne et al. 2003).

Three dimensions of water productivity include physical productivity, expressed in kg per unit of water consumed; combined physical and economic productivity expressed in terms of net return per unit of water consumed, and economic productivity expressed in terms of net income returns from a given amount of water consumed against the opportunity cost of using the same amount of water (Kijne et al. 2003). The discussion in the present paper would be largely on the first parameter, i.e., physical productivity. There are two major ways of improving the physical productivity of water used in irrigated agriculture. First: the water consumption or depletion for producing a certain quantum of biomass for the same amount of land is reduced. Second: the yield generated for a particular crop is enhanced without changing the amount of water consumed or depleted per unit of land. Often these two improvements can happen together with an intervention either on the agronomic side or on the water control side.

There are several conceptual level issues in defining the term 'water saving' and irrigation efficiency. This is because with changing contexts and interests, the 'unit of analysis' changes from field to farm, to irrigation system to river basin. With the concepts of 'dry' and 'wet' water saving, which capture the phenomena such as 'return flows from field' and 'depleted water', becoming dominant in the irrigation science literature in the last one decade, the old concepts of 'water saving' and irrigation efficiencies have become obsolete. The real water saving or the 'wet water' saving in irrigated production at the field level can come only from reduction in the depleted water and not the water applied (Molden et al. 2001). But, there are methodological and logical issues involved in estimating the depletion fraction of the water effectively applied to the crop. These are due to the complex considerations, including agronomic, hydrologic, geo-hydrological and geo-chemical, in determining the 'depletion' fraction. Nevertheless, for the limited purpose of analysis, throughout this paper, 'water saving' refers to 'wet' water saving.

Water productivity is an important driver in projecting future water demands (Amarasinghe et al. 2004; Kijne 2003). Efficient irrigation technologies help establish greater control over water delivery (water control) to the crop roots, reduce the non-beneficial evaporation from field and non-recoverable percolation,[1] and return flows into 'sinks' and often increases the beneficial ET, though the first component could be very low for field crops. Water productivity improves with the reduction in depleted fraction and yield enhancement. Since at the theoretical level, water productivity improvements in irrigated agriculture can result in saving water used for crop production, any technological interventions which improve the crop yields are also, in effect, water saving technologies. Hence, water saving technologies in agriculture can be broadly classified into three: water saving crop technologies; water saving and yield enhancing irrigation technologies; and, yield improving crop technologies.

There are several technologies and practices for water-saving in irrigation. But, only micro- irrigation technologies, which are based on plastics, are dealt with in this paper. India stands 27th in terms of the scale of the adoption of water-saving and yield enhancing micro-irrigation devices (source: www.oznet.ksu.edu/sdi/News/Whatisnew.htm). There are several constraints to the adoption of MI devices. These are physical, socioeconomic, financial, institutional—pricing, subsidies, extension service—and policy-related in nature (Narayanamoorthy 1997; Sivanappan 1994; Kumar 2003a). Nevertheless, a systematic attempt to find out the conditions under which MI systems become a best bet technology, and assess the magnitude of the reduction in water requirement possible through them is hardly ever made. Such efforts are crucial from the point of view of assessing our ability to address future water scarcity problems at the regional and national level.

The ultimate objective of this research is to find out under what conditions micro-irrigation system offers the best bet. It aims at determining the potential benefits from the use of MI systems. This includes assessing a) the conditions that are suitable or unsuitable for MI systems; b) the field level and aggregate level impacts of the systems on water use; and c) the yield and economic benefits due to the adoption of MI system. The research also aims at assessing the potential future coverage of MI systems in India, and the reduction in aggregate water requirement in crop production possible with that.

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[1] Allen et al. 1998 for definitions of non-beneficial evaporation and non-recoverable deep percolation.

Contribution of Micro-irrigation Technologies in Indian Agriculture

Present Spread of Micro-irrigation Technologies in Indian Agriculture

There were no systematic attempts in the past to assess the spread for water-saving irrigation technologies in India. The most recent data shows that nearly 1.3 m ha of irrigated land is under drip irrigation (Narayanamoorthy 2004b).

They cited high initial cost (including mis-targetted subsidies), clogging of drippers and cracking of pipes, lack of adequate technical inputs, damage done by rodents; high cost of spare components; and insufficient extension education effort as the major problems causal of the slow rate of adoption of drips. The National Committee on Irrigation and Drainage also added factors such as salinity hazards to the list of problems (GOI 1994). Difficulty in inter-cultivation was found as another reason for non-adoption by Shiyani et al. 1999, whereas Palanichamy et al. 2002 cited joint ownership of wells as additional reason for non-adoption based on their study in Coimbatore (Tamil Nadu). However, some of the problems listed above such as clogging, lack of adequate technical inputs and high cost of spare components, to a limited extent, are being by-passed with the introduction of low-cost micro-irrigation systems in India, pioneered by international development enterprises.

The recent data released by the Task Force on Micro-irrigation in India shows that during the past 4 years, peninsular India had recorded the highest growth in the adoption of drip systems. Maharashtra ranks first (22,358 ha), followed by Andhra Pradesh (17,556 ha) and Karnataka (16,731 ha). The major crops for which drip systems are currently adopted are cotton, sugarcane; banana, orange, grapes, pomegranate, lemon, citrus, mangoes, flowers, and coconut.

Though exact state-wise data on the spread of sprinkler systems are not available, it has been found that sprinkler systems are in vogue in regions where conditions are unfavorable for the traditional method of irrigation, such as loose sandy soils and highly undulating fields. These are well-irrigated areas. Farmers in other well-irrigated areas have also procured the system under the government subsidy program, but were found to be using the HDPE pipes for water conveyance in the field except during droughts when they are used for providing supplementary irrigation to *kharif* crops.

In India, sprinkler systems are mainly used for field crops such as wheat, sorghum, pearl millet, groundnut and mustard. But the use of sprinklers is often limited to certain parts of the crop season when farmers face severe shortage of water in their wells. Normally, this is just before the onset of monsoon when the farmers have to do sowing of these crops, or when there is a long dry spell during the monsoon season. Sprinklers for groundnut are common in Saurashtra in Gujarat; they are also common for mustard in Khargaon District of Madhya Pradesh and the Ganga Nagar District of Rajasthan. In the high ranges of Kerala and Tamil Nadu, sprinklers are used for irrigating tea and coffee plantations. However, recently, farmers have started using micro-sprinklers and mini-micro-sprinklers for potato, groundnut and alfalfa.

Potential Contribution of Micro-irrigation Technologies in India

Physical Impact of Micro-irrigation Technologies on Water Demand for Crop Production

Analyzing the potential impact of MI systems on the aggregate demand for water in crop production involves three important considerations. The first concerns the extent of coverage that can be achieved in MI system adoption at the country level. The second concerns the extent of real water saving possible with MI system adoption at the field level. The third concerns what farmers do with the water saved through MI systems, and the changes in the cropping systems associated with such adoption. But, most of the past research on physical impacts of MI systems had dealt with the issue of changes in irrigation water use, crop growth and crop yield.

There is limited analysis available on the potential coverage of MI systems in India, and the water saving possible at the aggregate level and these analyses suffer from severe limitations. First, the analyses of potential coverage of MI systems are based on simplistic considerations of the area under crops that are amenable to MI systems, and do not take into account the range of physical, socioeconomic and institutional factors that induce severe constraints to the adoption of these technologies. Second, they do not distinguish between saving in applied water and real water saving, while the latter possible through MI adoption could be much lower than the former. Third, there is an inherent assumption that area under irrigation remains the same and, therefore, the saved water would be available for reallocation. But, in reality, it may not be so. With the introduction of MI systems, farmers might change the very cropping system itself, including expansion in the irrigated area. Therefore, all these assumptions result in over-estimation of the potential coverage of MI systems and the extent of water-saving possible with MI adoption. These complex questions are addressed in the subsequent sections of this paper.

A) Physical Constraints and Opportunities for Adoption of MI Systems

Determining the potential coverage that can be achieved in MI system adoption requires a systematic identification of the conditions that are favorable or unfavorable for adoption and a geographical assessment of areas where such conditions exist. Such conditions can be physical, socioeconomic or institutional. These physical, socioeconomic and institutional constrains in the adoption of MI systems are discussed below.

If we do not consider the difficult options of shifting to less water-intensive crops and the crops having higher water productivity, there are two major pre-requisites for reducing the overall demand for water in agriculture in the region. They are i) reducing the non-beneficial evapotranspiration from crop land; and ii) maintaining the area under irrigation. The second issue is not dealt with here. The time-tested and widely available technology for increasing water productivity is pressurized irrigation systems such as sprinklers and drips (or trickle irrigation). However, their adoption is very low in India. While, there are several constraints at the field level, which limit the adoption of this technology by the farmer, some of the very critical ones that are physical in nature are analyzed here.

First of all, MI systems need a reliable daily water supply. But, nearly 41.24 % of the net irrigated area in the country gets their supplies from surface sources such as canals and tanks

(GOI 2002). Drips and sprinklers are not conducive to flow irrigation due to two reasons. First is the mismatch between water delivery schedules followed in canal irrigation and that to be followed when MI systems are used. Normally, in surface command areas in India, farmers get their turn once in 10-15 days at flow rates ranging from 0.5 to 1 cusec. But, for drips and sprinklers to give their best, water should be applied to the crop either daily or once in 2 days with lower flow rates equal to evapotranspiration. This means, intermediate storage systems would be essential for farmers to use water from surface schemes for running MIs. Storage systems are also required as settling tanks for cleaning large amounts of silt content in the canal water supplies. Second, there is a need for pumps for lifting water from the storage facilities and running the MI systems. These two investments would reduce the economic viability of MI.

Therefore, in the current situation the adoption of MI would be largely limited to areas irrigated by wells. Having said that, an increasingly large number of farmers in groundwater irrigated areas manage their supplies from water purchase. This also includes areas where groundwater overdraft is not a concern like in Bihar and western Orissa, and where economic access to water is a problem. It is difficult to imagine that these farmers would adopt any water saving irrigation devices.

MI systems are also energy-intensive systems and, therefore, need pressuring devices to run. Therefore, in groundwater over-exploited areas such as north and central Gujarat, Coimbatore District in Tamil Nadu and Kolar District of Karnataka, ownership of wells mostly does not remain with individual farmers but with groups. Also, a large number of farmers do not own wells, and have to depend on water purchase. They get water through underground pipelines at almost negligible water pressure (head). These farmers constitute a major chunk of the irrigators in the region. In order to use the conventional sprinkler and drip systems, high operating pressure (1.0-1.2 kg/cm^2) is required. Unless the systems are directly connected to the tubewell, the required amount of 'head' to run the sprinkler and drip system cannot be developed. The need for a booster pump and the high cost of energy required for pressurizing the system to run the sprinklers and drips reduce the economic viability. But, there are new MI technologies, which require very low operating head such as sub-surface irrigation systems and the micro-tube drips. The farmers who are either water buyers or share wells can store the water in small tanks and lift it to small heights to generate the required head for running the sub-surface drip system or micro-tube systems.

Another important constraint is the poor quality of groundwater. Due to the high TDS level of the pumped groundwater (the TDS levels are as high as 2,000 ppm (parts per million) in many parts of India where groundwater is still being used for irrigation), the conventional drippers that are exposed to sunlight get choked up due to salt deposition in the dripper perforations. The saline groundwater areas include south western Punjab, north and central Gujarat, parts of Rajasthan, and many parts of Haryana. This needs regular cleaning using mild acids like the hydrochloric acid. This is a major maintenance work, and farmers are not willing to bear the burden of carrying out this regular maintenance. However, in limited cases, rich farmers in South West Punjab use large surface tanks for storing canal water when it is available, and blend it with brackish groundwater, and use for irrigating *kinnow* (a kind of citrus) orchards. These farmers can also use this water for drip irrigation to prevent problems of clogging.

In addition to the areas irrigated by groundwater, there are hilly areas of the western and eastern Ghat regions, north-western Himalayas (Himachal Pradesh, J & K and Uttaranchal) and states in north-eastern hill region, where surface streams in steep slopes could be tapped for irrigating horticulture/plantation crops. Such practices are very common in the upper catchment areas of many river basins of Kerala, which are hilly. Farmers tap the water from the streams using hose pipes and connect them to sprinkler systems. The high pressure required to run the sprinkler system is obtained by virtue of the elevation difference, which is in the order of 30-40 meters. Such systems are used to irrigate banana, vegetables and other cash crops such as vanilla. With the creation of an intermediate storage, drips could be run for irrigating crops such as coconut, arecanut and other fruit crops during the months of February to June.

The geological setting has a strong influence on MI adoption in well-irrigated areas. In hard rock areas, farmers will have a strong incentive to go for MI systems. The reason is dug wells and bore wells in hard rock areas of Maharashtra, Madhya Pradesh, Tamil Nadu, Karnataka and Andhra Pradesh have very poor yield and well owners leave a part of their land fallow due to the shortage of water. In most of these areas, farmers will have to discontinue pumping after 2-3 hours for the wells to recuperate. When pressurized irrigation systems are used, the rate at which water is pumped decreases giving enough opportunity time for wells to recuperate. Since, the pump will eventually run for more number of hours, the same quantity of water could be pumped out, and the command area can be expanded. This factor provides a great economic incentive for farmers to go for water-saving micro-irrigation systems.

B) Socioeconomic and Institutional Constraints for MI Adoption

Another major constraint on the adoption of conventional MI technologies is the predominant cropping pattern in the water-scarce regions. MI systems are best adaptable for horticultural crops from an economic point of view (Dhawan 2000). This is because the additional investment for drips has to be offset mainly by the better yield, and the returns farmers get as the saving in input costs are not very significant. But, the percentage area under horticultural crops is very low in these regions, except Maharashtra. Though the low-cost drip irrigation systems appear to be a solution, they have low physical efficiency when used for crops in which the plant spacing is small (chilly, vegetables, groundnut and potato)—(source: IWMI research in Banaskantha). In such situations, they also score low in the economic viability front. The low-cost systems can be used for some of the row crops such as castor, cotton and fennel, which are very common. However, to use the system for these crops, it is very important that the farmers maintain a fixed spacing between different rows and different plants. So far as maintaining the spacing between rows is concerned, farmers pay sufficient attention. But, spacing between plants is not maintained. Due to this uneven (unfavorable) field conditions, designing and installing drippers becomes extremely difficult. Therefore, for the adoption of these water saving technologies, the farmers' agricultural practices need major changes.

Further, there are crops such as paddy for which neither drips nor sprinkler irrigation systems are feasible. Paddy is an important crop in many arid and semi-arid regions where water levels are falling. Certain studies at ICAR (Patna) have developed Low-Energy Water Application (LEWA) systems which apply regulated water supplies to paddy and have demonstrated potential to save water. But the technology is still in its infancy and requires large- scale testing before any field-scale adoption. Adopting suitable cropping patterns that would increase the adoptability of water-saving technologies is one strategy. But, as mentioned in the beginning of the section, 'crop shift' is a harder option for farmers.

The socioeconomic viability of crop shifts increases with the size of the operational holding of farmers. Given the fact that small and marginal farmers account for a large percentage of the operational holders in India, the adoptability of horticultural crops by farmers in these regions cannot be expected to be high. This is because these crops need at least 3-4 years to start yielding returns, (except for pomegranate and papaya). It will be extremely difficult for these farmers to block their parcel of land for investments that do not give any returns in the immediate future, say after a season or so. Market is another constraint. Large-scale shift to fruit crops can lead to sharp decline in the market prices of these fruits. Labor absorption is another major issue when traditional crops such as paddy, which are labor-intensive, get replaced by orchards. Orchards require less labor, it is also seasonal, and the chances for mechanization are higher.

Plot size also influences farmers' choices. Conventional MI systems will be physically and economically less feasible for smaller plots due to the fixed overhead costs of energy, and the various components of these irrigation systems such as filters and overhead tanks. Also, the additional energy required for running the system will decrease with every additional sprinkler, the reason being that only the pressure loss increases with the increase in the number of sprinklers/drippers (Kumar 2003a). However, organizations like International Development Enterprises (IDE) have developed and promoted MI systems for very smallholder farmers/ plots, which use small storage cisterns for providing the required pressure.

Poor rural infrastructure, mainly in respect of power connections to agro-wells and the quality of power supply, is another major constraint on the adoption of MI systems. Difficulty in obtaining power connections for farm wells, and the poor quality of power supply force farmers to use diesel pump sets for irrigating their crops. The use of diesel pumps increases the cost of abstraction of well water. Regions such as Bihar, eastern UP and Orissa are examples. Here, many cash-starved farmers do not own wells, and depend on water purchased from well owners for irrigation. Drips and sprinklers are energy-intensive systems, and installing such systems would mean extra capital investments on higher capacity pump sets as well as recurring expenses for buying diesel. These factors act as deterrents to adopting MI systems.

The current water pricing and energy pricing policies in most states also reduce the economic incentives for MI adoption. Due to these policies, the water-saving and energy-saving benefits that can be accrued from the use of MI systems do not get converted into private benefits.

Unscientific water delivery schedules followed in surface irrigation systems, and power supply restrictions on the farm sector also induce constraints on MI adoption. It is common in surface irrigation systems that while plenty of water is released for the crops during a certain part of the season, in the last leg of the crop season the crops are subject to moisture stress. Poor reliability of water delivery services or lack of adherence to standard delivery schedules and poor control over volumetric supplies force farmers to adopt crops that are less sensitive to water stress such as paddy and sugarcane and also resort to flood irrigation. Regulated power supply in agriculture is also reducing the economic incentive for the adoption of MI systems that are energy-intensive.

Poor extension services offered by concerned agencies pose another major constraint. It is not common for the extension wings of Agricultural Universities to set up demonstrations of new technologies in farmers' fields. This is applicable to companies which manufacture and sell MI devices. Because of this, there is very little knowledge about MI technologies among the farmers in water-scarce regions. The existing knowledge is filled more with misconceptions. Many farmers believe that MI systems have severe limitations vis-à-vis crops for which they could be used. Another misconception is that the coverage of sprinklers being circular leaves a lot of dry spots in the irrigated fields. This belief has mainly come from the experience of farmers who have used the system with improper designs.

The administration of subsidies in MI devices also works against the interest of promoting MI systems. Since in many states, the governments continue to pay the subsidy directly to the manufacturers, many farmers purchase MI systems just to avail themselves of the subsidy benefits, and do not maintain them. The suppliers do not to offer any after-sales services to the farmers and hence are not interested in ensuring quality control. The systems being supplied are often of substandard quality. Over and above, as the amount of funds available for subsidies is limited, the smartest of the farmers take the benefit. On the other hand, the government officials, who come and inspect the systems installed, only check the amount of materials supplied, and certify them for the release of the subsidy to the irrigation company. Since the manufacturers had the hassle of doing the entire documentation for obtaining the subsidy, they keep the price (without subsidy) high enough to recover their interests on capital and transaction costs.

The present institutional framework governing the use of groundwater, which puts no limit on the amount of water farmers can pump from the aquifer, does not provide clear economic incentives to use water efficiently. This is particularly so for well owners, who have good sources of water supply. Though it is the opportunity cost of using water, which influences farmers' decision-making framework, such opportunity costs are not felt clearly. This is in spite of the prevalence of water markets in these regions. The reason is that the demand for water from the water buyers and for ones own irrigation use, is much less than the number of hours for which the farmers could run their pumps. In such cases, the direct additional financial returns the farmer gets by introducing MI systems are from the increased crop yield. This will not happen unless the farmer adopts new agronomic practices.

Due to this reason, the well owners would rather pump for extra hours to sell water to the needy farmers than trying to use water more efficiently by making substantial capital investments. The reason is that the gain through the economic efficiency of water use for the irrigated crops grown in the area even with current inefficient practices is much higher than the price at which water is traded (Kumar and Singh 2001).

Presence of negative externalities in groundwater pumping poses an important constraint for those who like to adopt MI systems. Well interference is very common not only in hard rock areas, but also in shallow alluvial areas. Under such conditions, pumping by one farmer will affect the prospects of pumping by another farmer. Due to this reason, the efforts to cut down pumping rates by a farmer may not result in increased future availability of groundwater for him/her. The efforts to save water from the system by an individual farmer might mean increased availability of groundwater for pumping by his/her neighboring farmers. Hence, under such situations, the farmers do not have any incentive to invest in MI systems. The technical externality becomes negative externality for well irrigators in the absence of well-defined water rights for groundwater.

C) Real Water Saving and Water Productivity Impacts of MI Systems in the Field

The real water saving impact of MI systems at the field level depends on the improvements in water use efficiency. All the available data on the efficiency impact of micro-irrigation systems are on application efficiency. The classical definition of irrigation efficiency is the ratio of the amount of water consumed by the crop to the amount of water applied. Sivanappan 1994 provides the data on application efficiencies at various stages such as conveyance efficiency, field application efficiency and soil moisture evaporation. These figures do not take into account two factors:1) in certain situations, water will have to be applied in excess of the ET requirements if the irrigated soils have salts for the purpose of leaching; and 2) the actual field performance of the irrigation systems is not as good as that shown in experiments and demonstrations.

But in estimating water-saving, what matters is the amount of depleted water, rather than the amount of water applied. The depleted water includes moisture evaporation from the exposed soil and non-recoverable deep percolation. It would be less than the applied water so long as the unconsumed water is not lost in natural sinks like saline aquifers or swamps (Allen et al. 1998). This means, the application of the concept of irrigation efficiencies is no longer useful in analyzing the performance of irrigation systems, with a greater understanding of agro-hydrology and appreciation of deep percolation from irrigated fields[2] as a component of the available water resources (Keller et al. 1996), except in situations where the groundwater is saline or deep or the unconsumed water goes into swamps.

Water use efficiency improvements through MI adoption, and therefore the field level water-saving impacts, depend on three major factors: 1) the geo-hydrological environment, including the depth to the groundwater table and the nature of the aquifer, whether freshwater or saline; 2) the type of crops; and 3) the agro-climate.

In regions where the water table is deep and showing declining trends, MI adoption can lead to real water saving at the field level. The reason is deep percolation that occurs under the traditional method of irrigation, does not reach the groundwater table. This can be explained in the following way. The reason is that the depth of groundwater table is in the range of 20 m to 135 m. The 20-135 m thick vadose zone holds the vertically moving water as hygroscopic water and capillary water. Some of the water from the soil profile within or below the root zone, having higher levels of moisture, also can move up due to differential hydraulic gradients (Ahmed et al. 2004). All this water would eventually get evaporated from the crop land after the harvest if the fallow period is significant depending, on the climate. The depth of soil below the surface from which evaporation could take place can be up to 2-3 meters in semi-arid and arid regions (Todd 2003). Some water in the deep vadoze zone would get sucked away by the deep-rooted trees around the farms during the non-rainy season.

Since, under MI system, water is applied daily in small quantities to meet the daily crop water requirements, deep percolation is prevented. Such regions include alluvial tracts of north and central Gujarat, central Punjab, hard rock areas of northern Karnataka, Tamil Nadu, Andhra Pradesh, Maharashtra, Madhya Pradesh and many parts of Rajasthan. Though deep percolation could be quite significant in paddy irrigation, so far, no water-saving irrigation devices are being tried in paddy, though many water-saving practices have evolved over time in paddy irrigation.

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[2] Deep percolation is due to the drainage below the root zone, which can find its way to perched water table or true groundwater table. Deep percolation is common in all surface methods of irrigation such as border irrigation (both leveled and unleveled small and large border), furrow irrigation and flooding.

Nevertheless, in areas where groundwater levels are still within 20 meters below ground level, the saving in applied water achieved through MI devices would mostly result in saving in pumping cost, but no real saving in water from the system. The reason is that a good share of the excess water used in irrigation under the traditional irrigation practices finally goes back to the groundwater system through return flows. It is important to note that the areas having high water table conditions coincide with areas with low level of aridity or mostly sub-humid or humid climate where evaporation losses from soil would be low even in summer months.

The real water saving that can be achieved through MI system would be high under semi-arid and arid climatic conditions. This is because the non-beneficial depletion of moisture from the exposed soil could be high under such situation due to high temperature, wind speed and low humidity. Such losses would be significant during initial stages of crop growth when the canopy cover is small.

The real water saving would be more for row crops, including orchards, cotton, fennel, castor, and many vegetables, where the spacing between plants is large. The reason is the area exposed to solar radiation and wind between plants would be large, and as a result the non-beneficial evaporation would be a major component of the total water depleted, under traditional method of irrigation. With drip irrigation, water could be directly applied to plants, preventing this loss. Hence, the reduction in non-beneficial evaporation from soils and non-recoverable deep percolation, and hence actual water saving through micro-irrigation could be in the range of 10-25 % depending on the type of crops and the natural environment (soils, climate and geo-hydrology).

There are no scientific data available in India on the actual impact of MI systems on water use efficiency, which estimates the depleted water against the water consumed by the crop, or which takes into account the amount of water available for reuse from the total water applied. Sivanappan 1994 does not provide figures of ‘real water saving’. The extent of this would be determined by the climate (arid, semi-arid or sub-humid or humid), depth to the, groundwater table and groundwater quality, and the amount of water available for deep percolation.

There is effectively no research in India quantifying the real water saving and water productivity impacts of water saving irrigation technologies on various crops, at the field level. An extensive review of literature shows that all the data on water-saving are based on applied water, and within that, more reliable data are on experimental farms, for limited number of crops and system types and for a few locations. Data on water-saving, yield rise and water use efficiency improvements with drip irrigation over flood irrigation in several crops, which were compiled from experimental data from different research stations across India (INCID 1994; NCPA 1990) as cited in Narayanamoorthy 2004b: shows that the reduction in water consumption varies from a mere 12 % for ash gourd and bottle gourd to 81 % for lemon.

Some of the figures on water saving provided by INCID and NCPA are quite high. But, it is important to remember here that the condition of flood irrigation system chosen for comparison influences the findings on water saving and yield improvements in DMI (drip method of irrigation). Poorly managed flood irrigation systems used for comparison could significantly affect the result in favor of DMI. However, to obtain high efficiencies, surface methods (furrow, border, and basin) are generally demanding of operating skills and require a high degree of flexibility in water supply. In contrast, much of the complexity of drip and sprinkler irrigation systems is in their design rather than in their operation, and they can more easily be operated (but are not always) with low losses. Generally, the natural environment imposes constraints on realistically achievable efficiency levels (Carter et al. 1999)[3], and therefore in what environments the comparisons are made is also important. But, it is a truism that with the same technology, and with the same crop, the water saving and yield impacts of these irrigation technologies would depend on the agro-climate.

One major limitation of the database is that they are generated for a single location. Another limitation is that it compares DMI with one traditional method only. But, the extent of field level water saving through DMI would be heavily influenced by the conventional irrigation method practiced for that crop in the region under consideration, and the precision irrigation followed in drip irrigation. Flooding in large basins is just one of the many traditional irrigation methods used by Indian farmers. Its use is generally limited to canal irrigated fields, and fields irrigated by wells in canal command areas due to high flow rates from canals. The other methods are small border irrigation, trench irrigation and furrow irrigation, and are generally used by well irrigators.

Crops such as cotton, potato and groundnut are irrigated in furrow as well as small borders. Orchards are irrigated using trench irrigation. On-farm efficiencies are much higher under furrow, trench and small border irrigation as compared with flooding. Another limitation is that data obtained from experimental farms are for ideal conditions, and using such data can lead to over-estimation of field level water saving and water use efficiency impacts of DMI. The reason is it is difficult to simulate the ideal conditions of experimental farms in farmers' fields. For instance, in drip irrigation, the best results are obtained when water is applied daily. But, in actual field conditions, farmers may not be able to apply water daily due to irregular power supply and many other field constraints.

The rest of the data on field level water savings and yield improvements through MI systems are from socioeconomic studies based on respondent surveys involving adopters and non-adopters. The data on water saving are arrived at using figures of the total applied water. The available data from the experimental farms do not enable the analysis of reduction in depleted water under various treatments. Based on the earlier discussions, it is reasonable to assume that for traditional methods of irrigation, the 'applied water' would be very close to the depleted water for row crops. Under semi-arid and arid climatic conditions, there are no hard empirical data obtained from experiments to prove this. Here, one unknown parameter is deep percolation.

While MI systems are expected to have likely impact on deep percolation from the fields, such deep percolation can be treated as loss into the sink because of the following reasons: 1) drip irrigation is normally used in well-irrigated fields; 2) the amount of water percolating in non-paddy irrigated fields would normally be low (based on Ahmed et al. 2004), especially for well irrigation, as the dosage per watering is generally low; 3) the depth of vadoze zone in which the percolating water could be held as hygroscopic water or capillary water would be high in arid and semi-arid areas which depend on groundwater; and, 4) part of the water going into the vadoze zone can get lost in soil evaporation during the fallow period (based on Todd 2003). Hence, applied water saving which the available literature refer to can be treated as real water saving.

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[3] Soil types, climate and hydrology can affect water losses. Surface irrigation is likely to be more efficient on vertisols than sandy soils. Undulating or sloping land may dictate the use of drip or sprinkler irrigation which can then be managed with less water loss than surface techniques. Unpredictability complicates management and normally reduces efficiency. Total irrigation is easier to schedule and manage than supplementary irrigation because of the unpredictability of natural rainfall (Carteret al. 1999).

But, these studies are not complete in themselves, as they cover a few crops, and a few MI devices. Also, these studies have serious limitations. First, they are mostly based on data obtained from respondent surveys, which capture relative benefits of the technology from the farmers' perspective. Second, they are also likely to be influenced by respondents' bias. In order to understand the extent to which the water productivity of crops could be enhanced through MI technologies, it is crucial to get realistic data on potential changes in irrigation water use and crop yield, the two determinants of water productivity, with different technologies.

Field experiments conducted in Banaskantha District of Gujarat with different MI devices on various crops to analyze the impact of the technology on irrigation water use, crop yield and water productivity covered the crops alfalfa, castor, groundnut and potato. The technologies used are inline drip system for alfalfa; micro-tube drip with and without plastic and organic mulching, and flooding with and without plastic/organic mulching; micro-tubes and inline drippers for groundnut; and inline drippers and micro-tubes in potato.

The treatments used for alfalfa are different spacing of drippers without changing the water delivery through drippers (30 cm*40 cm in F1 to 50 cm*40 cm in F4); maintaining the same spacing of drippers (30 cm*30 cm) with different intensities of daily irrigation (G1 to G4); maintaining same spacing of drippers with different intensities of irrigation, and with watering on alternate days; and small level border irrigation with different intensities and with various irrigation schedules (from an average of 7-8 days in winter to 5 days in summer to an average of 6 days in winter to 4 days in summer). FYM was applied in all the plots in equal dozes, and no chemical fertilizers were used. The volume of water applied in the field was measured using water meters each time when irrigation is done, and output is weighted each time harvest/cutting is done.

The results show that the yield is the highest for plot with a dripper spacing of 30 cm* 40 cm (11.36 kg/m^2) of green matter, followed by one with a spacing of 35 cm*40 cm (10.71 kg/m^2). But, water productivity was the highest (7.8 kg/m^3 of water) for the plot which recorded the second highest yield (F_2). Therefore, the highest yield corresponds to a depth of application of 1.6 m, while the highest water productivity corresponds to a depth of 1.37 m. With flood irrigation, the yield values were the highest for treatment I_5 in which the amount of water applied was 4.3 m. Though these are very high figures for small border irrigation, it can be attributed to sandy soils. Here, I_1 is a case of over-irrigation with very heavy doses of irrigation (139 mm) and can be discarded. The figures are relevant in the sense that even with such high dozes of irrigation no field run off was generated, meaning there are chances for farmers to actually apply such high doses in sandy soils under well irrigation.

The yield figure almost touched that obtained with daily irrigation through drips (F_1 and F_2). But, the amount of water applied was far higher than that under F type treatments—almost three times in most cases. The water productivity values were in the range of 1.47 kg/m^3 and 2.79 kg/m^3, which were only 20 to 30 % of that obtained with drip irrigation under F_2 treatment. The results show that with drip irrigation, the water productivity could be enhanced significantly in alfalfa without compromising on the yield. As regards economic viability, even if we compare the drip irrigated plots with some of the best plots under flood irrigation, the reduction in water use is very substantial, with modest improvements in yield. Therefore, when water availability becomes a constraint, drip for alfalfa would be economically viable under a lateral spacing of 30 cm*40 cm. This is because, one of the earlier analysis with similar type of drip system on alfalfa showed that even with 10 % increase in yield, and 45 % reduction in water use, drips could be economically viable, when the social benefits of water saving are taken into account.

The results (I_1 to I_{10}) also show that there are significant variations in water productivity levels of alfalfa under flood irrigation with changing irrigation intensity. The highest yield was obtained under the second highest level of water application (4.33m over the full crop year). The highest water productivity (2.79 kg/m^3) was obtained with the lowest level of irrigation (3.15 m). The lowest water productivity (1.47 kg/m^3) was obtained under the highest level of irrigation (6.0 m).

Experiments were carried out with micro- tube drips with plastic and organic mulching and micro-tubes with broad furrows as the control in Manka Village of Vadgam in Banaskantha. There were four treatments followed. In the first three treatments, watering was done daily with daily irrigation water requirement estimated roughly on the basis of the crop water requirement (K_c*ET_0), and daily dosage was adjusted on the basis of the field observations of soil moisture conditions. In the fourth case, the irrigation water dosage was determined by making provision for evaporative losses from the exposed soil in the crop land and deep percolation losses. The scheduling was the same as that practiced in the area for castor for traditional method. While a total of 96 watering were done with C_1, C_2 and C_3, irrigation was applied nine times under C_4. The results showed that the water application rate was the lowest when micro-tube drips were used with plastic mulching (treatment C_1), followed by micro-tube with organic mulch (treatment C_2). The water application rate was highest for broad furrow treatment (C_4). The yield was the highest for C_1, followed by C_4. The water productivity was the highest for C_1, and the second highest for C_2. The difference in water productivity was in the order of 100 % between the first and the last treatment.

Experiments conducted on groundwater with inline drip systems and micro-tube drips showed the highest level of reduction in applied water use in the case of inline drippers when compared against border irrigation. The treatment included daily application of water to the plot through inline drippers and micro-tube drips. The fertilizer doses were same in all the plots which were of the same size. The reduction in water dosage was nearly 18 cm, while the yield was higher by 0.013 kg/m^2, with a net effect on water productivity in the order of 0.18 kg/m^3 of water. The micro-tube irrigated plot though gave same yield as that of furrow irrigated plot, the applied water was less with micro-tube. The study shows that the inline drippers are physically more efficient than furrow method and inline drip irrigation.

Another interesting experiment was done with different types of MI devices to understand the physical productivity of irrigation water in potato. In this experiment, five different types of MI devices were used, viz., inline drippers; easy drips (or drip systems with flexible laterals having a thickness ranging from 125 microns to 500 microns and having perforations instead of drippers to emit water); micro-tube drips; micro-sprinklers; and mini-sprinklers. The results showed that the yield and physical productivity of water is the highest for fields irrigated with micro-sprinklers, followed by mini-sprinklers. This is in spite of the fact that the water dosage was more than double in the case of treatments P4 and P5.

On the basis of the values of irrigation dosage and the corresponding yield and water productivity values under different treatments, one could infer that water dosage was much lower than required in the case of inline drip, easy drip and micro-tube drip irrigated plots, resulting in water stress and significant yield losses. Also, another inference is that in all the treatments, water dosage was in the ascending part of the yield and water productivity response curves for irrigation water application, which also means that with higher dosage of irrigation, the chances for getting higher yield are higher. It can be seen that with micro-tubes, though the amount of water applied was the same as that with inline drips (P1), the yield (0.148 kg/m^2) was much lower than that with P1. This could be due to poor distribution efficiency obtained with micro- tubes.

D) Potential Aggregate Impact of MI Systems on Water Use for Crop Production

There is debate about the extent of water saving at system and basin levels due to the widespread adoption of MI systems. This concerns: 1) whether there are real water savings in the first place; and, 2) what users do with the saved water. We have addressed the first question in the earlier section. As regards the second question, many scholars believe that the aggregate impact of drips on water use would be similar to what it makes on water use per unit area of land. While several others believe that with a reduction in the water applied per unit area of land, the farmers would divert the saved water for expanding the area under irrigation, subject to favorable conditions regarding water and equipment availability, and power supplies for pumping water (Kumar 2003a),.[4] and therefore the net effect of the adoption of micro-irrigation systems such as drips and sprinklers on water use could be nil or insignificant at the system level. At the same time, there are others who believe that with the adoption of WSTs, there is a greater threat of depletion of water resources, as in the long run, the return flows from irrigated fields would decline, while the area under irrigation would increase under WSTs.

These arguments have, however, missed certain critical variables that influence farmers' decision making with regard to the area to be put under irrigated production, and the aggregate water used for irrigation. They are groundwater availability vis-à-vis power supply availability; crops chosen; and the amount of land and finances available for intensifying cultivation. The most important of these factors is the overall availability of groundwater in an area; and the power supply situation vis-à-vis water availability in the wells.

If power supply restrictions limit pumping of groundwater by farmers, then it is very unlikely that as a result of the adoption of conventional WSTs, farmers would expand the area under irrigation. Let us see how this happens. In the states of Punjab, Gujarat, Karnataka and Madhya Pradesh, power supply to agriculture sector is only for limited hours (GOI 2002). It acts as a constraint on expanding the irrigated area, or increasing irrigation intensity, in those areas where groundwater availability and demand is more than what the restricted power supply can pump.

Since the available power supply is fully utilized during winter and summer seasons, farmers will be able to just irrigate the existing command with MI system. This is because the well discharge would drop when the sprinkler and drip systems connected to the well outlet start running, owing to the increase in pressure developed in the system. In other words, the energy required to pump out and deliver a unit volume of groundwater increases with the introduction of MI system. The only way to overcome this is to install a booster pump for running the MI system. As electricity charges are based on connected load, farmers have least incentive to do this. Such outcomes are expected in the alluvial areas of North Gujarat and

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[4] If power supply is more than what is required to pump the available water from wells, then water saving can lead to expansion in irrigated area. Whereas, if power supply is less than what is required to pump the available water from wells, then water saving per unit area cannot result in area expansion Kumar 2003a).

Punjab. In this area, even in situations where extra land is available, it won't be possible for farmers to expand the area under irrigated crops due to restrictions on power supply.

The other factor is the lack of availability of extra arable land for cultivation. This is applicable to areas where land use and irrigation intensity is already high. Central Punjab is an example. But, farmers might still adopt water-saving technologies for cash crops to raise yields or for newly introduced high-valued crops to increase their profitability. So, in such situations, adoption would result in a reduction in aggregate water demand.

On the other hand, if the availability of water in wells is less than what the available power supply can abstract, it is very likely that with the adoption of micro-irrigation systems, the farmers would expand the area under irrigation. This is the situation in most of the hard rock areas of peninsular India, central India and Saurashtra. Due to limited groundwater potential and overexploitation, well water is very scarce in these areas. The available power supply is more than what is needed to abstract the water in the wells and farmers have strong economic incentive to go for MI systems other than yield enhancement (Dhawan 2000). The reason is that the saved water could be used to expand the irrigated area and improve the economics of irrigated farming. In Michael region of central India, for instance, farmers use low-cost drips to give pre-sowing irrigations to cotton, before monsoon, when there is extreme scarcity of groundwater. This helps them grow cotton in a larger area as water availability improves after the monsoon (Verma et al. 2005), and hence there is no water saving at the aquifer level.

The third factor is the crops chosen. Often MI technologies follow a set cropping pattern. All the areas/pockets in the country where adoption of drip irrigation systems has undergone a 'scale', orchard crops are the most preferred crops (Dhawan 2000; Narayanamoorthy 2004b). Therefore, when farmers adopt MI systems, the crops also change, normally from field crops to fruits. While for many fruit crops, the gestation period is very large extending from 3–10 years (for instance, citrus, orange and mango), for many others like grapes, pomegranate and banana, it is quite short extending from 1–2 years. Also, farmers can go for intercropping of some vegetables and watermelon, which reduces their financial burden of establishing the orchards. This flexibility enables small and marginal farmers also to adopt MI systems, as found in North Gujarat and Jalgaon and Nasik districts of Maharashtra. Access to credit and subsidy further increases MI adoption among small and marginal farmers. The irrigation water requirement of the cropping system consisting of field crops such as paddy, wheat, pearl millet/sorghum combinations is much higher than that of fruit crops such as pomegranate, gooseberry, sapota and lemon. Also for other orchard crops such as mango, the irrigation water requirements during the initial years of growth would be much less than that of these field crops. Therefore, even with expansion in cropped area, the aggregate water use would drop. Only in rare situations, the system design for one crop is adaptable for another crop.

Economic Impacts of MI Systems

There is an enormous amount of research-based literature showing the positive economic impacts of water-saving irrigation devices. Many research studies available from India during the past one decade quantified economic benefits from drips.

Synthesizing, there is very little data across agro-climatic conditions on the yield impacts of micro-irrigation systems for the same crop. The research is heavily skewed towards drip irrigation systems, and there is hardly any data on the economics of other WSTs. As we have seen early, for a given crop, the yield as well as water-saving benefits of MI system could change across systems and so are the capital costs. Also, it could change across crops. But, the research is also heavily skewed towards orchard crops, banana, sugarcane and cotton. These crops still occupy a small percentage of the irrigated area in the country. Further, these economic analyses were not contextualized for the socioeconomic and institutional environment for which they were performed. The socioeconomic and institutional environments determine the extent to which various physical benefits get translated into private and economic benefits. We would explain it in the subsequent paragraphs.

Normally, it has been found that drip irrigation is economically viable for horticultural crops and orchards such as banana, grapes, orange, coconut, and sugarcane (Dhawan 2000 [pp 3,775]; Sivanappan 1994; Narayanamoorthy 2004b). The reason for this is that the crops are high valued and even a marginal increase in yield results in a significant rise in the value of crop output. Dhawan 2000 argues that the higher value of the crop output is realized also from improved price realization due to quality improvements on one hand and the early arrival of the drip-irrigated crop in the market on the other. The same need not be true for other cash crops, and field crops.

For instance, the income benefit due to yield improvement depends on the type of crop. For cereals, it cannot be significant. A 10 % rise in yield would result in an incremental gain of 400-500 kg of wheat or Rs.3,000-Rs.3,750 per ha of irrigated wheat. At the same time, a 10 % rise in the yield of pomegranate, whose minimum yield is 60,000 kg per ha per year, would result in an incremental gain of 6,000 kg/ha or Rs.90,000 per ha. Besides the incremental value of outputs, an important factor which influences the economic performance of the drip system is the cost of installation of the system.

From the point of view of deciding on the investment priorities including the provision of subsidies, it is important to know the social benefits from drip irrigation. As Dhawan 2000 notes, cost-benefit analyses, which do not take into account social costs and benefits, are on weak conceptual footing as the government subsidies in micro-irrigation systems are based on the premise that there are positive externality effects on society due to water saving. In areas, where available water in wells is extremely limited, it is logical to take water-saving benefits and convert the same in monetary terms based on market price or in terms of additional area that can be irrigated. Same is the case with energy saving. But the same methodology cannot be applied to areas where access to water is not a limiting factor for enhancing the area under irrigation, or energy is not a scarce resource.

Given the range of variables—physical, socioeconomic and financial—that affect the costs and returns from crops irrigated by MI systems, it is important to carry out comprehensive analysis taking into account all these variables, across situations where at least the physical, socioeconomic conditions change. Now, we would examine how these variables operate changes under different situations.

As regards water saving, in many areas, the well owners are not confronted with the opportunity cost of wasting water. Hence, water saving does not result in any private gains whereas in some hard-rock areas like Kolar District in Karnataka, the amount of water that the farmer can pump from the well is limited by the geo-hydrology. The price at which water is sold is also high in such areas (Deepak et al. 2005), and the opportunity cost of using water is high in those areas. Hence, the amount of water saved would mean income saving for the adopters.

As regards benefit due to energy-saving, it is applicable to certain MI devices, especially low pressure systems and gravity systems such as drip tapes, micro-tube drips and easy drips. But, farmers of many water-scarce regions are not confronted with marginal cost of using energy. Hence, for them energy saving does not result in any private gain. But, from a macro economic perspective, if one wants to examine the economic viability of the system, it is important to consider the full cost of supplying electricity to the farms while evaluating the economics of irrigation using the system. Also, we consider the price at which water is traded in the market for irrigation. and any saving in water resulting from drip use could be treated as an economic gain. The real economic cost of pumping water would range from Rs.1.5/m^3 in North Gujarat to Rs. 2/m^3 in Kolar District.

The private income benefit due to water saving is applicable to only those who purchase water on hourly basis. Dhawan 2000 cautions that over-assessment of private benefits are possible in certain situations where return flows from conventional irrigation are significant (Dhawan 2000 [pp 3,777]). But in regions where reduction in deep percolation means real water saving, it leads to private benefits. Here, for water buyers, the private income gain from the use of drip or sprinkler system depends on the price at which water is purchased (volumetric) and the reduction in water use achieved. There could be significant social benefits due to water saving in water-scarce regions, owing to the reduced stress on precious water resources (Dhawan 2000 [pp 3,775]), resulting from reduced pumping. In situations like North Gujarat, such social benefits could not be over-emphasized.

As regards the cost, the capital costs could vary widely depending on the crop. For widely spaced crops (mango, sapota, orange and gooseberry) the cost could be relatively low due to low density of laterals and drippers. For closely spaced crops such as pomegranate, lemon, papaya, grapes, the cost could go up. For crops such as castor, cotton, fennel and vegetables, the cost would go further up as denser laterals and drippers would be required. Even for low-cost micro- tube drips, the cost per ha would vary from Rs.12,000 for sapota and mango to Rs.28,000 for pomegranate to Rs.40,000 for castor.

Keeping in view these perspectives and situations, economics of water-saving technologies can be simulated for four typical situations for alfalfa in Banaskantha District of North Gujarat based on real time data collected from four demo plots in farmers' fields.

The first level of analysis is limited to private cost-benefits (level 1). Yield increase and labor saving are the private gains here. The annual yield benefit was estimated by taking calculated daily yield increase and multiplying it by 240, which is the approximate number of days for which the fodder field yields in a year. The labor-saving benefit was calculated by taking the irrigation equivalent (in daily terms) of total water saved (total volume of water saved/discharge of pump in 8 hours) and multiplying it by the daily wage.

In the second level of analysis, the actual economic cost of using every unit of electricity is considered as a benefit from saving every unit of the energy (level 2). In this case, the energy saving and cost saving depend on two factors: the energy required to pump a unit volume of groundwater, and the total volume of water saved. In the third level of analysis, the unit price of water in the market was treated as economic gain from the 'actual saving' of every unit of water and was added to the cost of electricity to pump a unit volume of water (level 3). This was multiplied by the total volume of water saved to obtain the total economic gain in excess of the gain from yield increase and labor saving. The fourth level of analysis concerns farmers who are irrigating with purchased water. Here in this case, the unit price of water could be considered as a private gain from saving every unit of water (level 4). In this case, the cost of constructing a storage tank and a 0.5 HP pump are added to the cost of installing the system. The private benefit-cost ratio ranged from 1.09 to 1.29; economic benefit-cost ratio (level 2), from 1.18 to 1.83; economic benefit-cost (level 3), from 1.28 to 2.78 and private benefit-cost for water buyers, from 0.88 to 1.39 (Kumar et al. 2004).

An analysis of economics of some water-saving technologies (pressurized drips, sprinklers and micro-tubes) was attempted on the basis of data on crop inputs and outputs, and capital investments collected from a primary survey on adopters and non-adopters in Kachchh, Bhavnagar, Rajkot and Banaskantha districts. The analysis is based on the estimates of incremental returns from drip irrigation over the entire life of the system against the additional capital investment for the system. For calculating the present value of an annuity, a discount rate of 6 % was used and the life of the system was considered as 10 years. The incremental returns considered are the average of two consecutive years. This was done to take care of the problems of yield reduction due to crop failure and price fluctuations. While estimating the incremental returns, the effect of differential input costs, and differential return were considered. The benefit cost analysis was carried out for three important crops in all the four districts irrigated by micro-irrigation systems.

In the case of Kachchh, the B/C ratio ranges from the lowest of 0.56 for castor to 6.0 for banana. Apart from castor, there was one more crop for which the B/C ratio was found to be less than 1.0. For all other crops, the B/C ratio was more than 1.0. In the case of Banaskantha, the B/C ratio ranged from 1.37 for *bajra* to 5.2 for castor. In the case of Bhavnagar, the B/C ratio ranged from 0.84 for *bajra* to 15.3 for mango. For crops in Rajkot, the B/C ratio ranged from 1.06 for chilly to 3.3 for cotton. Overall, two major findings emerge from the results of benefit-cost analysis. First, for cash crops and orchard crops, the B/C ratio often become very high but with wide variations across crops. For instance, in case of castor in Banaskantha, the B/C ratio is 5.2, whereas it is only 0.56 for the same crop in Kachchh. Second, for conventional field crops, the B/C ratios are generally low, but with low variation (Kumar et al. 2004).

It is noteworthy that the incremental net returns were generally markedly higher for cash crops viz., ground nut, cotton, castor; and fruits viz., mango and banana than for food crops viz., *bajra* and wheat. This is in conformation with the work of earlier researchers (Narayanamoorthy 1997; Sivanappan 1994). The incremental returns from cash crops, particularly fruits, could, however, fluctuate significantly depending on the price and yield fluctuations. At the same time, it is also equally striking to note that the benefit-cost ratios are good for even cereals given the fact that the capital cost of the system is high and the market value of the produce is not high. Perhaps, this could be due to the reason that the farmers, who did not use the system faced significant yield losses due to water stress.

Potential Future Benefits from Micro-irrigation Technologies

This section is based on inferences drawn from section two concerning the conditions under which micro-irrigation system becomes a good bet technology.

Water-scarce River Basins That Can Benefit from Micro-irrigation Technologies

Though the economic viability of MI systems for a given crop would depend on a wide range of factors, such as natural environment (soils and climate), production conditions, market conditions, spread of the technology in an area and the type of price considered for economic evaluation (whether, farm gate price or market price) due to paucity of data on the actual conditions for which the evaluation is performed, general conclusions are drawn on the conduciveness of the basins to the technologies based on the available data and the knowledge about the regions' physical and socioeconomic conditions and institutional settings.

That said, there are many basins that can benefit from MI devices. But, the extent to which it can contribute to overall improvement in basin water productivity would depend on 1) the total area under crops that are conducive to micro-irrigation devices in the basin; 2) the types of sources of irrigation of those crops, i.e., whether lift irrigated or gravity irrigated; 3) the climatic conditions in the basin; and, 4) the geo-hydrological conditions.

We have seen that the crops that are served by gravity irrigation are least likely to be covered under MI systems due to physical, socioeconomic and institutional constraints. Hence, large areas of Haryana, Uttar Pradesh, and Punjab offer no potential for scaling up of micro-irrigation systems as mostly they are covered under canal systems. Over and above, water saving irrigation devices are not conducive to paddy, one of the major crops grown in these areas, too. Though sprinklers can be used for wheat, the water-saving and yield impacts are not likely to be significant enough to motivate farmers to go for it. Nearly 55 % of the groundwater in Haryana is of poor quality with salinity and alkalinity, and the problems are more severe for deeper aquifers in the region. The use of groundwater for irrigation itself is marginal, making micro-irrigation system adoption difficult. In Bihar, leaving aside the problem of low appropriateness of the prevailing cropping system (comprising wheat and paddy), power crisis would be a major stumbling block for the adoption of sprinklers which are energy-intensive.

As regards climate, most of Gangetic-Brahmaputra-Megha basin covering most parts of Uttar Pradesh, Bihar, and north- east has sub-humid and cold climate, and the extent of water-saving possible through MI system adoption could be quite insignificant.

If we consider factors such as the physical availability of water, physical conditions of water supply and land use, cropping systems and groundwater table conditions, the basins where MI system adoption could take-off and where it would result in enhancement in basin level water productivity are west flowing rivers north of Tapi (river basins of Saurashtra, Kachchh and Luni in Rajasthan); Banas, Sabarmati, south-western parts of Punjab and Haryana in Indus; Cauvery Basin; Krishna Basin; Pennar Basin; Vaghai Basin; Narmada; downstream areas of Tapi; Mahanadi and Godavari.

The enhancement in water productivity would come from two phenomena: 1) Reduction in the amount of water depleted with no effect on crop consumptive use; and 2) Raising the yield of all the crops that are grown in these basins. Nevertheless, within these basins, there are areas where the groundwater table is very shallow, and climate is sub-humid. They include south and central Gujarat, which are in the downstream areas of Tapi and Narmada.

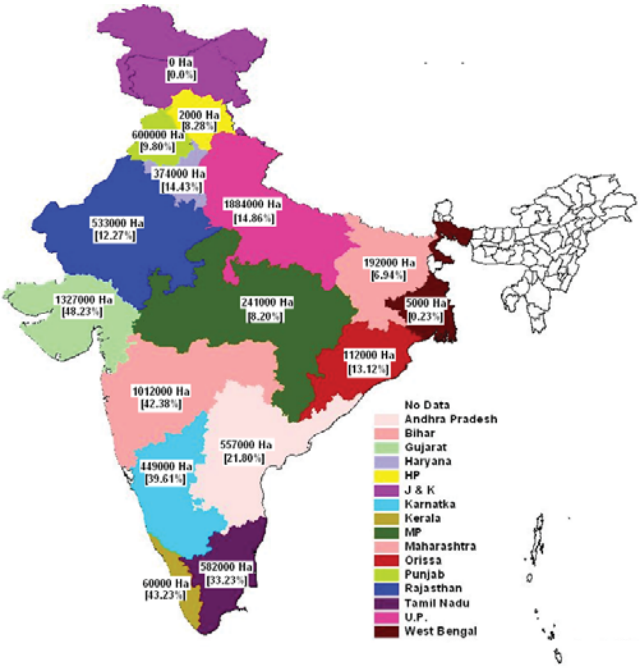
The western Ghat areas in Kerala, Karnataka, Maharashtra and Goa provide a very favorable environment for the adoption of micro-irrigation devices due to the presence of tree and fruit crops and plantation crops—coconut, arecanut, coffee, tea, mango and banana. The semi-arid, hard-rock areas of Tamil Nadu, Karnataka, Andhra Pradesh, Maharashtra and most parts of Gujarat, provide a favorable environment for the adoption of MI systems owing to limited groundwater potential; the dominance of well irrigation; and dominance of tree crops, fruit crops, cash crops, row crops and vegetables as mentioned above. At the same time, there would be real saving in water due to the fact that the groundwater table is falling in these regions.

The available data on the adoption of micro-irrigation systems in different states of India during the past 4 years is a testimony to what has been discussed in the preceding paragraphs. The highest area under drip irrigation is in Maharashtra (22,358 ha). This is followed by Andhra Pradesh (17,556 ha), Karnataka (16,731 ha) and Gujarat and Rajasthan. But, at the aggregate level, micro-irrigation accounts for nearly 1.6 % of India's total irrigated area, against 21 % in the United States, and 30 % (8 % under drips and 22 % under sprinklers) in Australia.

Area That Can Be Brought under MI Technologies in Major Indian States

Map 1 shows the area under different crops for which MI devices are conducive in different states of India. The empirical basis for estimating this constitutes: 1) the gross irrigated area under such crops; and 2) the percentage of net irrigated area under well irrigation in the respective states. Such approach has the inbuilt assumption that the percentage area under well irrigation is uniform across crops. This may not be true. In fact, it has been found that in surface irrigated areas, farmers normally take water-intensive, but less water-sensitive crops. It considered only 16 major states, and had excluded the minor states (13 nos.) and Union Territories. Further, it has excluded area under crops viz., wheat, mustard, rapeseed, pearl millet and sorghum which can be irrigated using sprinklers, but with poor results in terms of water-saving, and had included only those which are amenable to drips and plastic mulching.

Map 1. Estimated area under crops conducive to water saving irrigation technologies.



Note: Figures in parenthesis represent percentage area under the crop.

It shows that Uttar Pradesh has the largest area (1.884 M ha) under crops amenable to WSTs. It is followed by Gujarat with 1.327 M ha, and Maharashtra with 1.012 M ha.

Basins and Cropped Area Conducive to Adoption of Micro-irrigation Technologies

In order to estimate the figures for the 'total irrigated cropped area that would benefit from MI systems', we have superimposed the cropped areas for which MI systems are conducive, and the basins where MI adoption would lead to real water saving, and water productivity improvements. We would explain the logic behind this.

The earlier analysis has shown that peninsular and western India had a substantial area under crops that are conducive to MI technologies. It has also shown that central and north India have very little area under such crops. The exception is Uttar Pradesh, which accounts for nearly 25 % of the area that is conducive to MI systems. The basins in peninsular, western and central India have favorable natural environment comprising soil, geo-hydrology and climate due to which MI system adoption can actually result in real water saving, and basin level water productivity improvement. But, in Ganga-Brahmaputra basin, in which UP is, the adoption is going to be poor due to poor rural electrification; relative water abundance; shallow groundwater in most areas; and very low size of operational holdings of farmers. Even if this region adopts MI systems on a large-scale, it may result not in a reduction in depleted water, but a little difference in crop yields, with the resultant increase in basin level water productivity being meager. The western part of Mahanadi is another area that would be conducive to MI systems. Hence, Ganga-Brahmaputra-Meghna have to be excluded from our analysis.

Hence, the cropped areas that will benefit from MI system would be from: 1) basins of all east-flowing rivers of peninsular India; 2) basins of west-flowing rivers north of Tapi in Gujarat and Rajasthan; Mahanadi; 3) some parts of Indus Basin covering south-western Punjab; and 4) west flowing rivers of South India. Hence, the total would be 5.844 m ha (79.30-20.86) of cropped area. This is the absolute potential, and the real adoption would depend on several socioeconomic and institutional factors.

Now, let us look at the area estimates provided by Narayanamoorthy 2004b, and the task force on MI in India. Narayanamoorthy 2004b provided an estimate of 21.27 m. ha as the net area under all irrigated crops that can be brought under drip systems in India, with an upper figure of 51.42 m. ha including the area under those crops, which are currently rain-fed. But this analysis did not consider the several physical and socioeconomic factors that would ultimately determine the viability of drips for these crops. Whereas the task force on MI had estimated a figure of 69 m. ha as the area suitable for MI systems in India, it is quite clear from such a high figure that the task force estimates had included all regions and the area irrigated by different types of irrigation systems, therefore, has not considered the physical (technical, and hydro-meteorological), and socioeconomic constraints in the adoption of MI systems.

Quantification of Potential Future Impact of MI Systems on Water Requirements

In order to analyze the impact of MI devices on aggregate water requirement for crop production in India, we started with the data provided by INCID and NCAP where data on water use efficiency[5] impact of drip irrigation for various crops are presented. A total of six crops, for which country-level data on the irrigated crop area are available, were considered for estimating the future water-saving benefits. Then the data on aggregate output from these crops are obtained. Assuming that the same output for the respective crops is to be maintained in future, the future water requirement for growing the crops could be estimated by dividing the improved water use efficiency figures by the crop output.

The reduction in water requirement for crop $_i$= Present Output of Crop $_i$ [1/Current Water Productivity -1/Improved Water Productivity]

The procedure can be repeated for all crops.

While estimating the crop area that is likely to be brought under drips, the area under the respective crops in water-abundant states viz., UP, Bihar, West Bengal, Haryana and north eastern states was subtracted. The aggregate reduction in crop water requirement due to the adoption of drip systems was estimated to be 44.46 BCM (Table 1). It can also be seen that the highest water-saving could come from the use of drips in sugarcane, followed by cotton. This is the maximum area that can be covered under the crops listed in well-irrigated areas, provided all the constraints facing the adoption are overcome through appropriate institutional and policy environments. In the subsequent section, we would discuss what these policies are.

Table 1. Aggregate reduction in water requirement possible with drip irrigation systems.

Sr. no	Name of crop	Current yield (tonnes/ha)	Expected yield coming from the potential states* (million tonnes)	Water productivity (kg/m^3)	Improved water productivity (kg/m^3)	Water saving (BCM)
1	Sugarcane	128.0	170.0	5.950	18.09	31.00
2	Cotton	2.600	4.391	0.303	1.080	10.42
3	Groundnut	1.710	2.840	0.340	0.950	1.453
4	Potato	23.57	34.47	11.79	17.21	0.127
5	Castor	1.260	1.350	0.340	0.670	0.497
6	Onion	9.300	12.20	1.544	2.700	0.963
7	Total					44.46

Note: * States where MI systems are likely to be adopted. This is obtained by multiplying the average crop yield under conventional irrigation with the sum of the estimated area under that crop in each state. The water productivity figures are estimated from the yield and water consumption figures provided for the respective crops in INCID 1994 and NCPA 1990 as cited in Narayanamoorthy 2004b: pp 122.

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[5] We treat these water productivity values as the modified values of WUE capturing the net effect of improved water application and improved agronomic practices.

Institutional and Policy Alternatives for Spreading Micro-irrigation Technologies

The most ideal policy environment for the promotion of MI technologies in well-irrigated areas would be pro-rata pricing of electricity. While this would create direct incentive for efficient water use (Kumar 2005), the extent to which MI technologies would reduce energy use resulting in pro-rata pricing creating incentive for the adoption of MI devices depends on the crop type and the type of technology—whether pressurized system or gravity drip system—used for the crop. The reason is not all MI technologies are energy-efficient. Hence, bringing non-conventional (non-pressurized) drip systems under the ambit of subsidies is very important, once pro-rata pricing of electricity is introduced. It would also force farmers in areas irrigated by diesel engines to adopt such MI systems as it could save diesel and reduce input costs.

While in the long run, total metering and consumption-based pricing would be the most desired scenario to emerge (Kumar 2007), the government can start with metering of agricultural consumption. Cash incentives or heavy subsidy for MI devices could be provided to farmers who are willing to use them, subject to their minimizing the consumption of electricity. This cash incentive could be an inverse function of the total energy use for irrigation, and the percentage area under MI technology. This would create incentives for farmers to maximize the coverage of MI systems in their irrigated crops, particularly those which are less energy-intensive; and limit the total irrigated area.

Improving power supply conditions—both quality of power and hours of supply—is extremely important for boosting the adoption of pressurized MI devices in many areas. Such areas include alluvial North Gujarat and south-western Punjab. One could argue that with improved power supply, groundwater use could go up. But, in reality, with improved hours of power supply, the quality of irrigation would go up, enabling farmers to realize the full potential of MI systems. The actual impact of improved power supply regime on sustainability would depend on the type of crops farmers grow with MI systems, and the availability of extra land for area expansion. In areas where the entire cultivable land is under irrigation as in the tubewell commands of North Gujarat, and alluvial areas of central Punjab, the adoption of MI devices would result in reducing groundwater use at the farm level. MI adoption could result in farmers expanding the area under irrigation. Subsidies are required here to promote MI adoption as it would lead to social benefits from reduced stress on groundwater.

Improving the administration of subsidies is also of paramount importance to increase the welfare impacts. The farmers should be made to pay the full cost of the system initially, and subsidies released paid in installments based on periodic review of system performance. As manufacturers have to sell the system at the market price, it would compel them to improve the competitiveness of their products, and also provide good technical input services so as to sustain the demand. The rural credit institutions can advance loans to farmers for the purchase of MI systems so as to maximize the coverage of small and marginal farmers. In Gujarat, a new model for promoting MI devices is being implemented by the state government through a state-owned company called Gujarat Green Revolution Company (GGRC). Under this model, the subsidy is paid by GGRC to the farmer in installments, and the results are very encouraging. Not only that the adoption of MI devices is fast, but a significant percentage of the adopters belongs to smallholder category, having less than 2.0 ha of land, and they use it for cash crops viz., cotton, ground nut, potato and vegetables.

On the other hand, there is a need for creating a separate agency for promoting MI in each state to increase the speed of processing of application from farmers. The agency can work in tandem with the manufacturers and farmers to enable timely technical inputs to the farmers. In areas where agricultural processing units are concentrated, provision of all critical inputs including subsidies would not be a problem, as they could come from these processing units. An example is the sugarcane and grape grower cooperatives of Maharashtra. But, in areas where demand for drip irrigation is scattered vis-à-vis crops and geographical spread, this would be an issue. This substantiates the need for a separate agency. The agency should facilitate the survey of farmers' fields by the manufacturer, and get the designs and estimates prepared along with the most desirable cropping system. This would also help farmers procure the system well in advance of the crop season to make full benefit of it. Within a year after the creation of GGRC, a total of 30,000 ha of crop land had already been brought under drips in the state.

Summing Up

The adoption of MI systems is likely to pick up fast in arid and semi-arid, well-irrigated areas, where farmers have independent irrigation sources, and where groundwater is scarce. Further, high-average land-holdings, large size of individual plots, and a cropping system dominated by widely spaced row crops, which are also high-valued, would provide the ideal environment for the same. The extent of real water-saving and water productivity improvements at the field level through the adoption of MI systems would be high for widely spaced row crops, in arid and semi-arid conditions, when the groundwater table is deep or aquifer is saline. In hard-rock areas with poor groundwater potential, MI adoption would result in improved efficiency of water use, but would not reduce the total groundwater draft.

In semi-arid and arid areas which face severe groundwater scarcity, the economics of MI systems would be sound for high-valued cash crops. In areas where electricity charges are not based on power consumption, and the opportunity cost of using water is zero, the saving in energy and water achieved through MI system does not get translated into economic benefits. Hence, economics of MI system will not be sound in such areas. But, the evaluation studies are skewed towards drip systems, and do not capture the effect of changing physical, socioeconomic and institutional settings on the economic dynamic.

The future potential of MI systems in improving basin level water productivity is primarily constrained by the physical characteristics of basins vis-à-vis the opportunities they provide for real water-saving at the field level, and area under crops that are conducive to MI systems in those basins. Preliminary analysis shows very modest potential of MI systems to the tune of 5.69 m ha, with an aggregate impact on crop water requirement to the tune of 43.35 BCM possible with drip adoption for six selected crops. Creating appropriate institutions for extension, designing water and electricity pricing policies apart from building proper irrigation and power supply infrastructure would play a crucial role in facilitating large-scale adoption of different MI systems. The subsidies for MI promotion should be targeted at regions and technologies, where MI adoption results in real water and energy saving at the aggregate level.

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An Assessment of Environmental Flow Requirements of Indian River Basins

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Introduction

India faces a number of water related challenges, including increasing water scarcity and competition for water between different sectors and states. Some of the river basins in the southern and western states are experiencing physical or economic water scarcity. Basins in the east of the country are often perceived as having 'surplus' water and encounter recurrent floods. The National River Linking Project (NRLP) has been proposed as *the solution* to water related problems in India. The NRLP envisages transferring flood water of the Ganga, Brahmaputra and Meghna Rivers to the water scarce basins in the south and west (e.g., http://www.riverlinks.nic.in/). However, the NRLP is a contentious issue in Indian society, the media and amongst academics (e.g., Jain et al. 2005). Many scholars argue that the needs assessment of NRLP is inadequate. Others are of the view that the assessment of water surplus/deficits in Indian river basins, conducted as part of the NRLP proposal, has ignored environmental issues. Yet, others think that the very definition of "surplus water" needs to be clarified and that alternative water management options - less costly, easier to implement and more environmentally acceptable - have not been considered (e.g., Vaidyanathan 2003; http://www.lk.iwmi.org/nrlp/main; http://www.sdnpbd.org/river_basin/). Indeed, no assessment of ecological impacts of the future developments of water resources in the country seems to exist.

In India, as elsewhere in the world, freshwater and freshwater-dependent ecosystems provide a range of services for humans, including fish, flood protection, wildlife, etc. (e.g., Postel and Carpenter 1997; Revenga et al. 2000; http://www.maweb.org). To maintain these services, water needs to be allocated to ecosystems, as it is allocated to other users like agriculture, power generation, domestic use and industry. Balancing the requirements of the aquatic environment and other uses is becoming critical in many of the world's river basins as population and associated water demands increase. India is no exception. On the other hand, the assessment of water requirements of freshwater-dependent ecosystems represents a major challenge due to the complexity of physical processes and interactions between the components of the ecosystems. For day-to-day management of particular rivers, environmental requirements are often defined as a suite of flow discharges of certain magnitude, timing, frequency and duration. These flows ensure a flow regime capable of sustaining a complex set of aquatic habitats and ecosystem processes and are referred to as *"environmental flows", "environmental water requirements", "environmental flow requirements", "environmental water demand"*, etc. (Knights 2002; Lankford 2002; Dyson et al. 2003; Smakhtin et al. 2004a, 2004b). Many methods for determining these requirements have emerged in recent years. They are known as *environmental flow assessments* (EFA). The mean annual sum of estimated environmental flows represents a total annual water volume, which could be allocated for environmental purposes. In this report, we use the term 'environmental flows' (EF) to refer to the ecologically acceptable flow regime and the term 'environmental water requirements' (EWR) to refer to the total annual volume of EF.

The issues of EF assessment and management are high on the world agenda at present. At the same time, it remains a new research field. In many countries, including India, there has not even been a crude nationwide assessment of water requirements of rivers and their associated aquatic ecosystems. It is prudent to start addressing these issues which, in India, have become particularly relevant in the view of the major inter-basin water transfers planned under the NRLP.

This report starts with the description of India's physiography, water resources and water resources related problems. It proceeds by reviewing the emerging development of EF philosophy in India. It then reviews the current status of quick desktop EF estimation methods in the world and examines the applicability of those in the Indian context. It further formulates a simple EF assessment method which takes into account the limitations of available information in the country and illustrates its application using several major Indian river basins as examples. This is followed by recommendations on the immediate next steps in EFA in the context of the NRLP and for a longer-term EF research program.

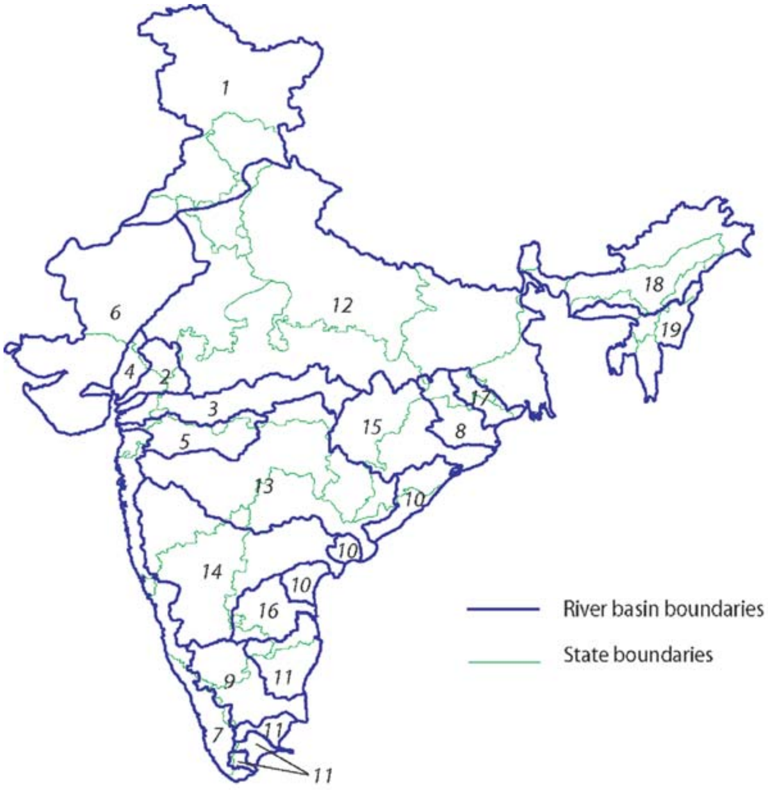
The study does not intend to give prescriptions for EF estimation in India or elsewhere. It suggests one potentially useful technique, which needs further development with more input from Indian hydrologists, aquatic ecologists, water engineers and other relevant specialists. The primary purpose of this work is therefore to stimulate the debate about EFA in India. It should be seen as a step towards the development of more detailed and comprehensive future national EF tools and policies and towards building the national capacity in the field of EFA. This study is a small component of a larger and longer-term research project which aims to assess multiple aspects of NRLP and the future of India's water resources in general.

Rivers in India

Hydrography

India has a large network of rivers, all of which are characterized by very large seasonal variation in their discharge due to seasonal rainfall and prolonged dry periods. The Indian mainland is drained by 15 major (drainage basin area >20,000 square kilometers [km^2]), 45 medium (2,000 to 20,000 km^2) and over 120 minor (<2,000 km^2) rivers, besides numerous ephemeral streams in the western arid region (Rao 1975). These river systems are traditionally grouped, according to their origin - into Himalayan and Peninsular rivers, or according to the direction of flow - into east flowing and west flowing rivers (NCIWRDP 1999; Amarasinghe et al. 2005). For large-scale analyses of water resources, the country is often separated into some 19 major river basins/drainage regions, which are shown in figure 1 (Amarasinghe et al. 2005). The main characteristics of these 19 river basins/drainage regions are given in Table 1.

Figure 1. A map of India, showing the boundaries of the major river basins/drainage regions and states.



River basins

1. Indus
2. Mahi
3. Narmada
4. Sabarmati
5. Tapi
6. West Flowing Rivers - group 1
7. West Flowing Rivers - group 2
8. Brahmani and Baitarani
9. Cauvery
10. East Flowing Rivers - group 1
11. East Flowing Rivers - group 2
12. Ganga
13. Godavari
14. Krishna
15. Mahanadi
16. Pennar
17. Subarnarekha
18. Brahmaputra
19. Meghna

Source: Amarasinghe et al. 2005

Table 1. Characteristics of the major river basins/drainage regions in India.

	River basin	Corresponding number in figure 1	Catchment area[a] (km^2)	Mean Annual Runoff[a] (BCM)
Basins of the West Flowing Rivers	Indus (to the border of Pakistan)[b]	1	321,000	73.3
	Mahi	2	35,000	11.0
	Narmada	3	99,000	45.6
	Sabarmati	4	22,000	3.8
	Tapi	5	65,000	14.9
	WFR1	6	334,000	15.1
	WFR2	7	113,000	201
Basins of the East Flowing Rivers	Brahmani and Baitarani	8	52,000	28.5
	Cauvery	9	81,000	21.4
	EFR1	10	87,000	22.5
	EFR2	11	100,000	16.5
	Ganga	12	861,000	525
	Godavari	13	313,000	110
	Krishna	14	259,000	78.1
	Mahanadi	15	142,000	66.9
	Pennar	16	55,000	6.3
	Subarnarekha	17	29,000	12.4
East India	Brahmaputra	18	194,000	585
	Meghna	19	42,000	48.4

Notes: [a] based on NCIWRDP 1999

[b] Indus system includes the river Indus and its tributaries: Jhelum, Chenab, Ravi, Beas and Sutlej

WFR1 = West Flowing Rivers - group 1 (rivers in Kutch and Saurashtra districts of Gujarat and the Luni River)

WFR2 = West Flowing Rivers - group 2 (rivers south of Tapi)

EFR1 = East Flowing Rivers - group1 (rivers between Mahanadi and Pennar basins)

EFR2 = East Flowing Rivers - group 2 (rivers between basins of Pennar and Kanaya kumari at the southern tip of India)

BCM = Billion Cubic Meters

Climate and Flow Regimes

The Indian climate is marked by a large spatial and temporal variability in precipitation, and a large potential evapotranspiration. There is considerable spatial variation in the Mean Annual Precipitation (MAP) which ranges from about 100 millimeters (mm) in the western Rajasthan State to more than 2,500 mm in Northeastern areas with a maximum of some 11,000 mm near Cherrapunji. High MAP values (over 2,000 mm) are also typical to the western slopes of the

Western Ghats. This, coupled with a variety of geological and topographical conditions of the river basins, results in a large spatial variability of flow regimes ranging from rivers flowing from the Himalayan Mountains and partially fed by snowmelt in spring and summer to alluvial plains' rivers, which receive considerable base flow from groundwater in autumn (Bandyopadhyay 1995).

Most of the rainfall in India takes place under the influence of the southwest monsoon between June to September except for the Tamil Nadu State, which is primarily impacted by the northeast monsoon during October and November. It is estimated that in Himalayan Rivers, where some flow is attributed to snowmelt, about 80 percent of the total annual flow takes place within the four southwest monsoon months. In Peninsular Rivers, where there is no contribution from snowmelt, monsoon flow accounts for more than 90 percent of the annual flow. Agrawal (1998) suggests that the entire annual rain in basins of the semi-arid tropics may fall within 100 hours, which is reflected in river flow regimes.

Degradation of Rivers

Since independence, India has witnessed rapid urbanization, industrialization, and intensification of agriculture, which all affected the rivers in different ways. Most Indian rivers, at present, are highly regulated (Agrawal and Chak 1991). Hundreds of multi-purpose reservoirs for water supply, irrigation, hydropower and fisheries have been constructed, as well as numerous barrages for water diversion. Many floodplains have been cut out from rivers by embankments and remaining riparian lands are under intensive agriculture and grazing pressure. Human settlements, deforestation, mining and other activities have degraded the river catchments and increased sediment loads of all rivers. Also, during the past few decades, rivers have received increasingly large discharges of industrial effluents, fertilizers and pesticides from agricultural practices and domestic wastes (CPCB 1996). All this affected riverine biota. Species composition has changed and many species have nearly disappeared. The loss of feeding and breeding habitats in the floodplain water bodies due to the construction of embankments (Mukherjee 2005), and increased silt load and macrophytic growth are major causes for declining fish resources (Jhingran 1991). It is symptomatic that out of the 30 world river basins marked as global level priorities for the protection of aquatic biodiversity by Groombridge and Jenkins (1998), nine (9) are from India due to their extensive and continuing development. These basins include Cauvery, Ganges-Brahmaputra, Godavari, Indus, Krishna, Mahanadi, Narmada, Pennar and Tapi. With an exception of Ganges-Brahmaputra, all the above basins have also been categorized as "strongly affected" by flow fragmentation and regulation (Nilsson et al. 2005).

Conservation and restoration of rivers have become vital for the overall sustainable development of the country. However, until recently, this "conservation" has been limited to "cleaning" of rivers by treatment of wastewater, occasional symbolic removal of garbage and enforcing the treatment of industrial effluents (Gopal and Chauhan 2003). So far, these efforts have not resulted in major improvements. Overall, there has been limited appreciation of the nature of rivers as ecosystems whose ecological integrity depends upon their physical, chemical, biological characteristics and interactions with their catchment.

Environmental Flows in the Indian Context

Development of Environmental Flow Philosophy

As in much of the world, Indian water planning and management considered water flowing to the sea as ‘wasted’. The approach was to harness river waters through dams and other structures to the extent that was technically feasible. Even the *new* National Water Policy (MOWR 2002) still ranks “ecology” as the fourth item in the list of priorities for water-allocation. As the progressive degradation of the water environment became evident, environmental concerns have started to gain strength. This is, perhaps, where and when the term ‘minimum flow’ originated from. Minimum flow was understood as a flow, which is needed (to be released) downstream from the dams for environmental maintenance. As the term implies, such releases were minimal. In fact, there is no documented evidence suggesting that such releases were actually made.

The first National Workshop on Environmental Flows, held in New Delhi in March 2005, brought together over 60 participants from national agencies and research institutions and highlighted a great interest in the concept of environmental flows in India. Several relevant studies and activities currently conducted in the country have been presented and the issues of terminology were high on the agenda.

Iyer (2005) suggested that expressions such as “environmental flows” or “water for nature” imply that in allocating water for different uses, an allocation must be made “for nature as well”. This may be seen as inappropriate in principle because “water itself is part of nature and one cannot presume to allocate water to nature”. Therefore, aquatic ecology should be seen as a user of the highest priority. Ecological considerations may impose constraints on other uses of water and ecological imperatives must guide the water-use and water resources development of the future. Iyer (2005) further pointed out that while the idea of a “minimum flow” or “environmental flows” in streams and rivers is welcome in so far as some flow is better than no flow, this may not necessarily imply any major change in thinking; abstractions and diversions continue to be the norm and “minimum flow” clearly implies maximum abstraction. If “environmental flow” is understood as a synonym of “minimum”, then the only change is in semantics. He further suggested that impacts on rivers are quantified against a reference condition of “natural flow”, which, for all practical purposes could be accepted as the flow which existed prior to major river regulation. Most of the above statements are similar to that of Silk et al. (2000) or to the philosophy adopted in South Africa, for the protection of aquatic ecosystems, whereby EF – known as ‘ecological Reserve’ - are estimated for a water body first. Then only the difference between the total available water resource (natural flow) and the Reserve is considered to be utilizable. Such school of thought represents a very pro-environment position and is unlikely to succeed, in the short-term, in a country without strong pro-environmental traditions and practices in the conditions of increasing water scarcity.

Iyer (2005) also advocated the importance of distinguishing between in-stream flows for different purposes: “Flows are needed for maintaining the river regime, making it possible for the river to purify itself, sustaining aquatic life and vegetation, recharging groundwater, supporting livelihoods, facilitating navigation, preserving estuarine conditions, preventing the incursion of salinity, and enabling the river to play its role in the cultural and spiritual lives of the people.” The latter appears to be a very important component in the Indian context (Sharma 2005), as water is necessary, amongst others, for cultural festivals and reduced flows can lead to depreciation of some religious places (e.g., Sinha and Prasad 2005). While several in-stream flow needs listed above can be satisfied by the same flow at the right time simultaneously, it appears important to agree on what ‘ecological flows’ or ‘environmental flows’ actually include. Mohile and Gupta (2005) suggested that requirements for drinking water, commercial fisheries, livelihoods and navigation as well as water for dilution of effluents are not included as part of EF, but rather considered as water for people, livelihoods and industries and estimated separately. As for effluents, they should be treated at source.

Mohile and Gupta (2005) also examined a wider concept of environmental water requirements and suggested that it should include the requirements of both terrestrial and aquatic ecosystems. The former would include direct evapotranspiration through forests, wetlands and other lands, all supporting distinct ecologies, while the latter would then be understood as EF. This is an interesting view given first, that the requirements of terrestrial ecosystems are currently not explicitly considered, and, second, that at present the ‘*environmental flow requirements’* and *‘environmental water requirements’* are normally taken as synonyms (except rare cases when EWR is used to denote the total volume of EF (e.g., Smakhtin et al. 2004a)). At the same time, expanding the term EWR beyond the requirements of aquatic ecosystems will only add confusion to the already existing terminology. The issues of water requirements of terrestrial ecosystems are not considered in this report.

Previous Environmental Flow Assessment Work and Related Activities

The status of EF research in India at present may be characterized as being in its infancy. The National Commission for Integrated Water Resource Development Plan (NCIWRDP 1999) effectively accepted that it was not possible to estimate the amount of water needed for environmental purposes. They pointed out that the knowledge base for making any approximate calculation of this requirement was very limited. A provisional projection of the environmental needs has been given as 5 cubic kilometers (km^3), 10 km^3 and 20 km^3 in the years 2010, 2025 and 2050, respectively. The reason for such growth is unclear, but less important in the context of the fact that overall the water requirement for ‘environment and ecology’ has been estimated at about 2 percent of the total national water requirements. The values given were not referenced to rivers, wetlands or groundwater and were just bulk volumes for the entire country without any geographical specification. The NCIWRDP ‘estimates’ do not appear to be based on any scientific reasoning.

The issue of minimum flow was highlighted in a judgment of the Supreme Court of India, which in 1999 directed the government to ensure a minimum flow of 10 cubic meters per second (m^3/s) in the Yamuna River as it flows through New Delhi for improving its water quality. Since then the minimum flow requirement in rivers has been discussed at several forums (but primarily in the context of water quality). In 2001, the Government of India constituted the Water Quality Assessment Authority (WQAA) which in turn constituted, in 2003, a Working Group (WG) to advise the WQAA on ‘minimum flows in rivers to conserve the ecosystem’. Despite the continuous use of the term ‘minimum flow’, the emphasis on ‘ecosystem’ is noteworthy (Prof. B. Gopal, NIE, personal communication). The WG reviewed the existing EFA practice and suggested that due to a variety of reasons, including the high hydrological variability, difficult tradeoffs between environment and agriculture, expensive waste treatment, disputes for water between States, etc., the practices adopted in other countries for assessment of EF are unlikely to be applicable in India. The WG also suggested that only a simple method (like Tennant, see section: *Review of Environmental Flow Assessment Methods*) may be adopted for estimating 'minimum flows' to be maintained in the rivers in India. These flows would primarily serve the purpose of maintaining prescribed water quality standards.

Perhaps, the first scientific attempt to assess EF for entire India has recently been done in the report by Amarasinghe et al. (2005). This estimate is based on the global study conducted by Smakhtin et al. (2004a; 2004b) and was made separately for major river basins/drainage regions in India, as shown in figure 1. The estimate turned out to be about 476 km^3, which constitutes approximately 25 percent of the total renewable water resources in the country. This, however, was not in fact an estimate of EF *per se*, but rather an estimate of the total volume of EF (i.e., EWR). The approach was based on hydrological data simulated by a global hydrological model, which was not calibrated for Indian conditions. No observed flow data from Indian rivers were used and no ecological data were present in the approach, although the hydrological hypotheses used were ecologically based. Also, it was an estimate representing only one scenario of environmental management – that all major river basins are maintained in "fair" conditions as explained in Smakhtin et al. (2004a).

The known attempts to approach the issue of EF in India (CWC, WG on Minimum Flows; Amarasinghe et al. 2005) addressed it at the scale of the entire country. More detailed, basin-specific EF research has not yet been initiated. One known exception is the project carried out by the National Institute of Hydrology (NIH) at Roorkie aiming at the EFA in the Brahmani-Baitarani River System (Table 1; Figure 1), where a hydrology-based Range of Variability Approach of Richter et al. (1997) (see section: *Review of Environmental Flow Assessment Methods*) is used. Preliminary recommendations for the Baitarani River have been formulated based on the need to maintain 7-day minimum and 1-day maximum flows in the river and its water quality within its current state (R. Jha, NIH, Roorkie, personal communication). This and some other EF-related activities in India are yet to be documented.

Review of Environmental Flow Assessment Methods

Basic Principles

'Environmental Flows' is a very simple concept. First of all, this term should always be used in plural, implying that a synonym to environmental flows is *an ecologically acceptable flow regime* designed to maintain a river in an agreed or predetermined state. Therefore, second, EF are a compromise between water resources development, on one hand, and river maintenance in a healthy or at least reasonable condition, on the other. Another useful way of thinking about EF is that of 'environmental demand' similarly to crop water requirements, industrial or domestic water demand. Despite the simplicity of the concept, difficulties arise in the actual estimation of EF values. This is primarily due to the inherent lack of both the understanding of and quantitative data on relationships between river flows and multiple components of river ecology.

Ecologists agree that the major criteria for determining EF should include the maintenance of both spatial and temporal patterns of river flow, i.e., the flow variability, which affect the structural and functional diversity of rivers and their floodplains, and which in turn influence the species diversity of the river (Ward and Tockner 2001; Ward et al. 2001; Knights 2002). Thus, EF should not only encompass the *amounts* of water needed, but also *when and how* this water should be flowing in the river. All components of the hydrological regime have certain ecological significance (Knights 2002). High flows of different frequency are important for channel maintenance, bird breeding, wetland flooding and maintenance of riparian vegetation. Moderate flows may be critical for cycling of organic matter from river banks and for fish migration, while low flows of different magnitudes are important for algae control, water quality maintenance and the use of the river by local people. Therefore, many elements of flow variability have to be maintained in a modified-EF-regime.

The focus on maintenance of flow variability has several important implications. First, it moves away from a 'minimum flow attitude' to aquatic environment. Second, it effectively considers that aquatic environment is also 'held accountable' and valued similarly to other sectors – to allow informed tradeoffs to be made in water scarcity conditions. Because wetland and river ecosystems are naturally subjected to droughts or low flow periods and can recover from those, then building this variability into the picture of EFA may be seen as *environmental water demand management.* This brings us back to the issue of 'compromise' and implies that EF is a very pragmatic concept: it does not accept a bare minimum, but it is prepared for a trade. Bunn and Arthington (2002) have formulated four basic principles that emphasize the role of flow regime in structuring aquatic life and show the link between flow and ecosystem changes:

- Flow is a major determinant of physical habitat in rivers, which in turn is the major determinant of biotic composition. Therefore, river flow modifications eventually lead to changes in the composition and diversity of aquatic communities.
- Aquatic species have evolved life history strategies primarily in response to the natural flow regimes. Therefore, flow regime alterations can lead to loss of biodiversity of native species.
- Maintenance of natural patterns of longitudinal and lateral connectivity in river-floodplain systems determine the ability of many aquatic species to move between the river and floodplain or between the main river and its tributaries. Loss of longitudinal and lateral connectivity can lead to local extinction of species.
- The invasion of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. Inter-basin water transfers may represent a significant mechanism for the spread of exotic species.

Major Categories of Environmental Flow Assessment Methods

Many EFA methodologies, which directly or indirectly encompass the above principles, have emerged in recent years. They differ significantly in accuracy and required input information. The discussion of these techniques may be found in many published sources including reviews by Jowett (1997), Tharme (2003), Acreman and Dunbar (2004) and is not repeated here. Different EFA methods should be used for different purposes – from general water resources planning to managing dam releases. In some countries, there is a move towards hierarchical multi-tier

EFA frameworks, driven by the availability or access to resources, including data, time, technical capacity and finances (http://www.dwaf.gov.za; Dyson et al. 2003). The two major tiers include:

- Detailed assessment, using primarily holistic methods, or methods based on habitat modeling
- Desktop, rapid assessment, using primarily ecologically relevant hydrological characteristics (indices) or analysis of hydrological time series

Methods from the first group often adopt a whole-ecosystem view in assessing EF, whereby ecologically and/or socially important flow events are identified and an ecologically acceptable flow regime is defined by a multi-disciplinary panel of experts. These methods include substantial amounts of field work and may take significant amounts of time (e.g., 2 to 3 years for a basin like Krishna – due to the need for ecological data collection at certain times of the year and the mere size of the basin) and resources to complete for a single river basin (e.g., King and Louw 1998; King et al. 2003). Habitat models, also included in this group are different from holistic methods, as they primarily focus on fish. However, they are very complex and also require a lot of input data and field work. They are used to assess the impacts of changing flow regime on physical habitat for key life stages of target fish species. Flow-habitat models quantify changes in physical in-channel hydraulic characteristics arising from flow regulation. Hydraulic output is combined with the physical habitat preferences of target species (e.g., Parasiewicz and Dunbar 2001). Both the habitat modeling approach and some holistic methods (e.g., King et al. 2003) are designed to address trade-offs. They are naturally suited to scenario analysis and are commonly used where negotiation is a feature of EF setting.

Methods from the second group - desktop EFA - are much more diverse, more suitable for initial, reconnaissance or planning-level assessments of EF. They can take a form of a look-up table (e.g., Tennant 1976; Matthews and Bao 1991) or be based on the detailed analysis of hydrological time series (e.g., Richter et al. 1997; Hughes and Hannart 2003). The look-up tables take a significant amount of time to develop, before they can be used, while the methods based on the time series naturally require either observed or simulated discharge time series (or both).

The number of available EFA techniques is sometimes grossly overstated (Tharme 2003). Most of them are simple hydrological indices which have existed and been used in various hydrological and water resources applications for decades. However, the number of ‘genuine’ EFA techniques continues to grow thus reflecting the quest for a better technique which suits the specifics of a particular task, region, data available, importance of an ecosystem and many other factors. Any classification of EFA methodologies is, however, rather arbitrary and different authors sometimes use different categories to refer to the same method (compare, for example, Dunbar et al. 1996; and Tharme 2003).

Regardless of the type of the EFA methods, all of them have been designed and/or applied in a developed country context. Distinct gaps in EF knowledge and practice are evident in current approaches to water resources management in almost all developing countries, including India, most of which lack technical and institutional capacity to establish environmental water allocation practices (Tharme and Smakhtin 2003). The existing EFA methods are either complex and resource-intensive (holistic approaches) or not tailor-made for the specific conditions of a particular country, region or basin (desktop methods).

The above ‘classification’ into comprehensive (detailed) and planning-type (desktop) methodologies, is therefore useful in the context of this study as most of the discussion below is focused on the second type - quick desktop EFA methods. The use of such methods may be seen as the starting point towards the understanding of EF and their importance in principle. While such methods provide estimates of low confidence (due to the lack of ecological data involved), they may be used to set the feasible limits for future water resource exploitation. Their application may change the still dominant perception about the insignificance of environmental water allocations in river basin planning and about the very nature of such allocations.

Desktop Environmental Flow Assessment Methods

The first example from this group is the Tennant method, which attempts to separate *a priori* the entire range of the Mean Annual Runoff (MAR) at a site of a river into several ecologically relevant ranges. All suggested ranges correspond to different levels of aquatic habitat maintenance or degradation and have been justified by observations in many streams in the USA. A threshold of 10 percent of the MAR reserved for an aquatic ecosystem was considered to be the lowest limit for EF recommendations (corresponding to severe degradation of a system). Fair/good habitat conditions could be ensured if 35 percent of the MAR is allocated for environmental purposes. Allocations in the range of 60 to 100 percent of the MAR represent an environmental optimum. This technique is still widely used in North America (Tharme 2003), but is somewhat outdated by now and is scientifically weak as a threshold selection (% of the MAR) is arbitrary and no flow variability is accounted for. One positive aspect of Tennant is the awareness that 10 % of the MAR may be considered the lowest and highly undesirable threshold for EF allocations and that at least some 30 % of the total natural MAR may need to be retained in the river throughout the basin to ensure fair conditions of riverine ecosystems.

Another frequently cited hydrological EFA technique is the Range of Variability Approach (RVA)(Richter et al. 1997), which aims to protect a range of flows in a river. The 32 hydrological parameters, which jointly reflect different aspects of flow variability (magnitude, frequency, duration and timing of flows), are estimated from a natural daily flow time series at a site of interest. It is further suggested that in a modified (ecologically acceptable) flow regime, all 32 parameters should be maintained within the limits of their natural variability. For each parameter, a threshold of one standard deviation from the mean is suggested as a default arbitrary limit for setting EF targets in the absence of other supporting ecological information.

The RVA may be applied as a desktop EFA tool. It can ensure that sufficient water is available for human uses and effectively accepts that the full range of natural streamflow variability will not be possible to maintain in regulated or otherwise affected river systems. However, despite the relatively advanced nature of the RVA, the number of parameters used in it is too large for the level of subjectivity associated with their selection. In addition, many parameters are either likely to be correlated with each other, or there is little difference between their values. Smakhtin and Shilpakar (2005) justified and illustrated the simplification of this technique through a significant reduction of the number of parameters. At the same time, even the simplified RVA approach requires a great deal of hydrological data (daily flow time series, which are not readily available - see section: *Developing a Prototype Desktop Environmental Flow Assessment Tool*) and, ideally, ecological data (for better setting of acceptable thresholds on parameters). It should be possible, for pilot assessment, to use monthly instead of daily flow data, select a limited number of flow parameter values and develop a stepwise decrement procedure for each of these parameters. This could effectively lead to a new, much simpler method, where all flow parameters are estimated by the same principle and data requirements are consistent with availability (at least in the Indian context at present).

The environmental water allocation procedures practiced by UK Environment Agency (2001) are known as CAMS (Catchment Abstraction Management Strategies). This allocation is determined through consideration of four elements: (i) physical characterization; (ii) fisheries; (iii) macrophytes; and (iv) macro-invertebrates (e.g., Acreman 2002). Each element is given a score from 1 to 5 based on its sensitivity to reductions in flow. In terms of physical characterization, rivers with steep gradients and/or wide shallow cross-sections score 5, since it is assumed that small reductions in flow result in a relatively large reduction in wetted perimeter. At the other extreme, lowland river reaches that are deep are assumed to be less sensitive to flow reduction and score 1. Scoring for fisheries is determined either by flow-habitat modeling, or by using *expert opinion* to classify the river according to description of each of the score classes. Once a score for each of the four elements has been defined, the scores are combined to categorize the river into one of the five environmental weighting Bands, where Band A is the most sensitive (mean score of 5) and Band E is the least sensitive (mean score of 1).

The next stage in CAMS is the definition of a target *flow duration curve* (FDC) that guides the setting of limits on abstraction (Petts 1996). First, a naturalized FDC is produced, either by a deterministic process of adding abstractions and subtracting discharges from a recorded flow time-series or by a regional steady-state model based on catchment characteristics (area, geology) and climate. A set of simple tabulated rules is then used to determine the percentage of natural low flow that can be abstracted, depending on the environmental Bands defined above. A low flow is defined as the flow exceeded 95 % of the time (95 *percentile on the FDC*). Rules for determining percentage of allowable abstractions at other flow *percentiles* at FDC are also provided. In this way, an entire target *environmental FDC* can be derived. The output figures are based largely on *professional judgment* of specialists, since critical levels have not been defined directly by scientific studies at present. Any such figures are open to revision, but with no clear alternative, this provides a pragmatic way forward. The entire procedure provides a first level estimate and any catchment may then be subjected to a more detailed analysis using habitat simulation models or other, more detailed methods (Parasiewicz and Dunbar 2001; Extence et al. 1999). This is effectively, an example of a two-tier approach mentioned earlier.

Perhaps the most advanced existing hydrology-based desktop EFA method has been developed by Hughes and Münster (2000) and further refined by Hughes and Hannart (2003). It is known as the ‘Desktop Reserve Model’ (DRM). The ‘ecological Reserve for rivers’ is effectively a South African term for ‘environmental flows’ (there are also procedures developed for the determination of ecological reserve for wetlands, estuaries and aquifers). Quantifying the ecological Reserve involves determining the volumes and discharges which will sustain a river in a predetermined condition. The latter is referred to as an ‘Ecological Management Category’ (or Class) – EMC (or, more recently, ‘Level of Ecological Protection’ - LEP) and is related to the extent to which this condition deviates from the natural. There are four LEPs - A, B, C, and D - where A rivers are largely natural and D are largely modified. These categories are determined by a sophisticated *scoring system* based on a number of indicators related to river importance and sensitivity.

The DRM originates from the Building Block Methodology (BBM) (King and Louw 1998). 'Building Blocks' (BBs) are environmental flows, which jointly comprise the ecologically acceptable, modified flow regime. The major BBs are low flows, small increases in flow ('freshes') and larger high flows, which are required for floodplain flooding and for river channel maintenance. BBs are defined for each of the 12 calendar months and differ between 'normal years' and 'drought years'. The first are referred to as 'maintenance requirements' and the second as 'drought requirements'. The set of BBs, therefore, include maintenance low flows, maintenance high flows, drought low flows and drought high flows.

The DRM uses similar BBs and was developed as a rapid, low confidence EFA approach. The basis for the model was an extrapolation of higher confidence EWR determinations (with specialist inputs from ecologists and geomorphologists) using the hydrological characteristics of the river flow regimes. Hughes and Münster (2000) analyzed the results of previous *comprehensive EFAs* of South African rivers in the context of hydrological variability of these rivers, and developed empirical equations which related the above BBs with flow variability and EMCs (Hughes and Münster 2000). The main variability characteristic - hydrological variability index - is calculated from the coefficients of variation (standard deviation/mean) of several calendar month flows and the baseflow index (baseflow contribution divided by total flow). The higher the variability index, the more variable is the river flow regime.

The main result of this analysis and the basic assumption of the DRM is that the rivers with more stable flow regimes (a higher proportion of their flow occurring as baseflow) may be expected to have relatively higher environmental low flow requirements in normal years ('maintenance low flow requirements' in Reserve terminology). Rivers with more variable flow regimes would be expected, from a purely hydrological perspective, to have relatively lower maintenance low flow requirements and/or lower levels of assurance associated with them. *The consequence of these assumptions is that the long-term mean EWR would be lower for rivers with more variable flow regimes*. The DRM therefore explicitly introduces the principle of 'assurance of supply' into EFA. The estimated BBs are then combined into a time series of EF using a set of assurance rules and the natural flow time series.

The underlying concepts of the DRM are attractive and, to an extent, ecologically justified, as they emerge from the results of comprehensive EFAs, which involve a variety of ecological disciplines. Smakhtin et al. (2004a, 2004b) have used the principles behind the DRM in their *global* assessment of EWR. One stumbling block for direct DRM applications in other countries (e.g., in India) is that regional DRM parameters have been estimated on the basis of South African case studies, but are not generally available for other areas. Symphorian et al. (2002) used DRM to study reservoir operation for environmental water releases in Zimbabwe, where hydrological conditions are similar to South Africa. The DRM has recently been tested for several rivers in England (M. Acreman, CEH, personal communication) while Smakhtin et al. (2006) attempted to use DRM in Nepal. In both cases, the general conclusion was that the direct application of DRM or any other desktop EFA method outside of the region, it was originally developed for, requires recalibration in new conditions. One possible alternative is to simplify the DRM so that the use of regional parameters can be avoided, while the main principles are retained. One additional advantage of the DRM is that it is originally based on *monthly flow data* which are more readily available or accessible in developing countries like India.

Implications for Future Environmental Flow Assessment in India

There are different ways of developing EF research and environmental water allocation practices in a country with limited exposure to EF concepts, like India at present. It is possible to develop a simple prototype assessment tool which illustrates the main EF concepts and allows preliminary EFA to be made in real river basins, using available national data. This should also allow unsound past practices/concepts (e.g., 'minimum flow') to be gradually left behind and further development of planning EFA tools to be stimulated, with input from the national eco-hydrological community. This approach would build the EF-related expertise and prepare a ground for more comprehensive, detailed and resource intensive EFA in the future.

Alternatively, EF-related capacity can be built through national workshops, which would aim to undertake detailed EF studies in specific national river basins and use the expert opinion of local ecologists and hydrologists who know their rivers. Even if this knowledge is not 'EF tailor made', and the results are uncertain, attempting such comprehensive EFA develops team building and interactions between experts in different disciplines.

Both approaches are complementary. The very limited time available for the current study, speaks in favour of the first approach, which may also be seen as a stimulus for more EFA tool development, more comprehensive EFA studies in the future and as a starting point for capacity building in EFA overall.

The above review of desktop EFA methods highlights several important considerations for the development of a prototype EFA method for India.

- To sustain ecological processes and associated animal and plant communities in river freshwater ecosystems, it is necessary to maintain ecologically relevant elements of natural hydrological variability (e.g., frequency, duration, magnitude of some flows, etc.). *Therefore, the method has to take flow variability into account.*

- *The method has to be commensurate with the current level of understanding of river ecology and flow data available.* The simpler and less information consuming the better at this stage. This allows EF issues to be explicitly highlighted for some or most of the major river basins in India within a short-term. Given the extreme level of uncertainty and data limitations in which this study is conducted, the method to be developed should be seen as a 'rule of thumb', be as generic as possible to form the basis for future refinement and application for river basins of various sizes.

- In most of the desktop methods, EF depend upon the category of protection in which a river ecosystem needs to be maintained. The closer this category to the natural state of an ecosystem, the higher the EWR should be and the more elements of natural flow variability should be preserved. While these categories are simply a management concept, it facilitates desktop EFA and allows preliminary EF estimates to be made. *It is therefore logical to design a prototype desktop EFA method so that it relates flow variability, conservation category and EF.*

- As evident from the above review, *all* existing EFA methods (comprehensive or desktop) *leave a lot to professional judgment or expert opinion,* which means that a strong scientific basis is not always present, even in detailed approaches and they remain essentially subjective. For example, various scoring systems are commonly used to determine current ecological status or the desired level of environmental protection of a river basin or reach. In the absence of other alternatives this allows expert knowledge to be formalized and 'quantified' and also brings at least limited ecological information/consideration into the EFA. *If existing ecological knowledge is limited and the scale of the EFA is coarse, aggregate environmental indicators, which reflect different features or conditions of a river basin, could be used for scoring.*

Developing a Prototype Desktop Environmental Flow Assessment Tool

Observed Flow Data

One primary aspect associated with the desktop EFA method development and application is the *observed flow data*. Due to the need to relate hydrological characteristics to EWR, the availability, type and quality of observed flow data determines how reliable the EFA method could be. Considering that *daily* flow time series carry much more information about flow variability and that monthly flow data can naturally be calculated from daily values, *the daily flow time series are always the preferred data type.* The reality, however, is that almost no daily flow time series are publicly available in India, and when the data are made available their quality appears to be low.

The lack of daily flow data may not be a major problem in itself as some EFA methods (e.g., DRM) successfully work with good quality monthly flow data. The minimum requirement for desktop EFA application at any site in a river basin is therefore *sufficiently long (at least 20 years) monthly flow time series reflecting, as much as possible, the pattern of natural flow variability*. However, the availability of monthly flow data in India is also limited. Some monthly flow time series for Peninsular Rivers (primarily for the last 15-20 years) have been provided by the Central Water Commission (CWC) of India. Additional monthly flow data (for years prior to the 1980s) for several Indian rivers may be downloaded from several websites on the Internet (these sites also contain data on other world rivers):

(i) http://www-eosdis.ornl.gov/

(ii) http://dss.ucar.edu/catalogs/ranges/range550.html

(iii) http://webworld.unesco.org/water/ihp/db/shiklomanov/index.shtml

(iv) http://grdc.bafg.de/servlet/is/Entry.987.Display/

The data available at these sites for Indian rivers are the same and therefore do not help to expand the available observed dataset. The origin of these data is also not specifically indicated but it is most likely that they have been provided by the Indian government to the international community in the past in the context of some global water resources assessment project(s).

Most of the monthly flow time series available from the Internet are very short (1 to 8 years), ending in the early 1980s or late 1970s and with many gaps due to missing data. They are therefore largely unsuitable for any meaningful hydrological analysis. The data found on the Internet therefore have been considered for use only if the total number of months without missing data was over 120. This allowed stations with a minimum of 10 years of observations to be included (if they had no missing data), or stations with longer records to be included (even if they still had some missing data). In any case, such selection has been based on an arbitrary *minimum, which is effectively below the requirements stipulated above.* In summary, over 50 monthly flow time series (acquired from CWC and the Internet) for various river basins were considered for use. Due to severe data limitations described above, only a few of those were finally selected (Table 2).

Simulating Reference Hydrological Conditions at the Outlets of Major Basins

The desktop EFA method suggested and tested in this study is built around a period-of-record FDC and includes several subsequent steps. The first step is the calculation of a representative FDC for each site where the EWR are to be calculated. In this study, *the sites where EF are calculated are coincident either with outlets of the major river basins or with the most downstream flow observation station.* The sites with observed flow data are further often referred to in this report as 'source' sites. The sites where reference FDC and time series are needed for the EF estimation (e.g., basin outlets) are further referred to as 'destination' sites. The destination sites are either ungauged or significantly impacted by upstream basin developments. Therefore, representative 'unregulated' monthly flow time series, or corresponding aggregated measures of unregulated flow variability, like FDCs, have to be simulated/derived from available observed (source) records.

Any FDC can be represented by a table of flow values (percentiles) covering the entire range of probabilities of occurrence. All FDCs in this study are represented by a table of flows corresponding to the 17 fixed percentage points: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent. These points (i) ensure that the entire range of flows is adequately covered, and (ii) easy to use in the context of the following steps. For all source sites listed in table 2, FDC tables were calculated directly from the observed record or from part of the record which could be considered 'unregulated'. Normally the earlier part of each record - preceding major dams' construction - was used to ensure that monthly flow variability, captured by the period-of-record FDC, is not seriously impacted.

For each destination site, a FDC table was calculated using a source FDC table from either the nearest or the only available observation flow station upstream. To account for land-use impacts, flow withdrawals, etc., and for the differences between the size of a source and a destination basin, the source FDC is scaled up by the ratio of 'natural' long-term mean annual runoff (MAR) at the outlet and the actual MAR calculated from the source record. The application of such ratio effectively 'naturalizes' the observed flow source time series and 'moves' it to the basin outlet. The estimates of 'natural' MAR for major rivers are available from Indian sources (e.g., Table 1). The estimates of 'natural' MAR for smaller basins in India could be obtained by means of hydrological regionalization (e.g., Kothyari and Garde 1991; Kothyari 1995).

The scaling up of the curves is effectively equivalent to the scaling of the actual time series. It is important to stress that both the calculated FDC and the corresponding time series reflect the flow amounts and variability which no longer exist at the outlets of river basins. They are perceived to represent the hydrological reference conditions that existed in the past prior to major basin developments.

Table 2. Details of selected observed monthly flow data sets.*

Lat DD. decimal	Long DD. decimal	River	Location	Area (km^2)	Record Period	Comment
26.1	91.7	Brahmaputra	Pandu	405,000	1956-1979	Missing data patched using the mean monthly flow. No recent data available. The entire record was used as an indicator of reference ‘natural’ flow variability.
12.4	76.6	Cauvery	Krishnaraj Sagar	10,600	1934-1979	Missing data patched using the mean monthly flow. The earliest part of the record (1934-1957) was used as an indicator of ‘natural’ variability.
10.8	78.8	Cauvery	Musiri	66,243	1990-2002	An indicator of present day hydrology
24.8	87.9	Ganga	Farakka	951,600	1949-1973	Missing data in 1961-1964 patched. No recent data available. The entire record was used as an indicator of reference ‘natural’ flow variability.
16.5	81.5	Godavari	Davlaishwaram	299,300	1901-1979	The record was used as an indicator of reference flow variability.
N/A	N/A	Godavari	Polavaram	307,880	1990-2005	An indicator of present day hydrology
16.5	80.6	Krishna	Vijayawada	251,360	1901-2005	The earlier part of the record (1901-1959) is used as an indicator of reference ‘natural’ flow variability, the latest – as an indicator of present day hydrology.
N/A	N/A	Mahanadi	H. K. Sambalpur	83,400	1926-1956	The record was used as an indicator of reference flow variability.
N/A	N/A	Mahanadi	Basantpur	57,780	1990-2003	An indicator of present day hydrology
22.3	73.0	Mahi	Sevalia	33,670	1968-1979	No recent data available. The record was used as an indicator of reference flow variability.
21.9	73.6	Narmada	Garudeshwar	89,345	1948-2004	The earlier part of the record (1948-1970) was used as an indicator of reference flow variability, the latest – as an indicator of present day hydrology.
22.2	76.0	Narmada	Mortakka	67,000	1948-2001	The record 1980-2001 is an indicator of present day hydrology.
14.6	80.0	Pennar	Nellore	53,290	1965-1979	No recent data available. The record was used as an indicator of reference flow variability.
21.3	72.9	Tapi	Kathore/Ghal	63,325	1923-2004	The earlier part of the record (1939-1979) was used as an indicator of reference flow variability, the latest as an indicator of present day hydrology.
10.2	76.7	Periyar	Planchotte	5,387	1967-1979	Example of a ‘small’ river from the West Coast. Located in the south of the WFR2 drainage region (table 1). No recent data available. Record is used as an indicator of reference flow variability.
23.1	73.4	Sabarmati	Ahmedabad	12,950	1968-1979	No recent data available. Record is used as an indicator of reference flow variability.
23.0	85.0	Subarnarekha	Kokpara	N/A	1964-1974	No recent data available. Record is used as an indicator of reference flow variability.

*Most of the data were used to simulate reference monthly flows at the ungauged basin outlets with the subsequent EWR estimation from simulated time series. Shaded rows show stations with observed data which were used for comparison with estimated EWR.

Defining Environmental Management Classes

EF aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition/ status also referred to as “desired future state”, “environmental management class”/ “ecological management category”, “level of environmental protection”, etc. (e.g., Acreman and Dunbar 2004; DWAF 1997). This report uses the term ‘environmental management class’ (EMC). The higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation and more flow variability will need to be preserved.

Ideally, these classes should be based on empirical relationships between flow and ecological status/conditions associated with clearly identifiable thresholds. However, so far there is insufficient evidence for such thresholds (e.g., Beecher 1990; Puckridge et al. 1998). These categories are therefore a management concept, which has been developed and used in the world because of a need to make decisions in the conditions of limited lucid knowledge. As shown in the review section (see section: *Review of Environmental Flow Assessment Methods*), placing a river into a certain EMC is normally accomplished by expert judgment using a scoring system. Alternatively, the EMCs may be used as default ‘scenarios’ of environmental protection and corresponding EWR and EF - as ‘scenarios’ of environmental water demand.

Six EMCs are used in this study and six corresponding default levels of EWR may be defined. The set of EMCs (Table 3) is similar to the one described in DWAF (1997). It starts with the *unmodified and largely natural conditions* (rivers in classes A and B), where no or limited modification is present or should be allowed from the management perspective. In *moderately modified* river ecosystems (class C rivers), the modifications are such that they generally have not (or will not – from the management perspective) affected the ecosystem integrity. *Largely modified* ecosystems (class D rivers) correspond to considerable modification from the natural state where the sensitive biota is reduced in numbers and extent. *Seriously and critically modified* ecosystems (classes E and F) are normally in poor conditions where most of the ecosystem’s functions and services are lost. Rivers which fall into classes C to F would normally be present in densely populated areas with multiple man-induced impacts. Poor ecosystem conditions (classes E or F) are sometimes not considered acceptable from the management perspective and the management intention is always to “move” such rivers up to the least acceptable class D through river rehabilitation measures (DWAF 1997). This restriction is not however applied in this report, primarily because the meaning of every EMC is somewhat arbitrary and needs to be filled with more ecological substance in the future. Some studies use transitional EMCs (e.g., A/B, B/C, etc.) to allow for more flexibility in EWR determinations. It can be noted, however, that ecosystems in class F are likely to be those which have been modified beyond rehabilitation to anything approaching a natural condition.

It is possible to estimate EWR corresponding to all or any of the above EMCs and then consider which one is best suited/feasible for the river in question, given existing and future basin developments. On the other hand, it is possible to use expert judgment and available ecological information in order to place a river into the most probable/achievable EMC. As evident from the above reviews of EFA methods, this approach is widely practiced. One can think of an ‘*ecological water report card’* for a basin. Such a ‘report card’ could include answers to the following three broad questions:

- The first question is: *what is the ecological sensitivity and importance of the river basin?* The rational for this is that the higher the ecological sensitivity and

Table 3. Environmental Management Classes (EMC) and corresponding default limits for FDC shift.

EMC	Ecological description	Management perspective	Default FDC shift limits
A: Natural	Pristine condition or minor modification of in-stream and riparian habitat	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions, etc.) allowed	Lateral shift of a reference FDC one percentage point to the left along the time axis from the original FDC position
B: Slightly modified	Largely intact biodiversity and habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed	Lateral shift of a reference FDC one percentage point to the left along the time axis from the position of the FDC for A class
C: Moderately modified	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present	Multiple disturbances associated with the need for socio-economic development, e.g., dams, diversions, habitat modification and reduced water quality	Lateral shift of a reference FDC one more percentage point to the left along the time axis from the position of the FDC for B class
D: Largely modified	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation	Lateral shift of a reference FDC one more percentage point to the left along the time axis from the position of the FDC for C class
E: Seriously modified	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem	High human population density and extensiv water resources exploitation	Lateral shift of a reference FDC one more percentage point to the left along the time axis fromthe position of the FDC for Dclass
F: Critically modified	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern, river habitats, etc (if still possible/ feasible) – to ‘move’ a river to a higher management category	Lateral shift of a reference FDC one more percentage point to the left along the time axis from the position of the FDC for E class

importance of aquatic ecosystems in a river basin, the higher the environmental category should ideally be.

- The second is: *what is the current condition of aquatic ecosystems in the river basin?* The more pristine the current condition of the basin, the more incentive in some cases could be to keep it that way. On the other hand, the current condition would determine to a large extent what EMC is achievable.
- The third is: *what is the trend of change?* This question aims to identify whether a river is still changing, how fast and due to what impacts. It may be seen as an attempt to foresee how the river will look like in the short-term (e.g., 5 years) and in the long-term (e.g., 20 years) in case of a ‘do-nothing-to-protect-aquatic-environment’ scenario. The rational is that if deterioration of aquatic environment still continues it will be more difficult to achieve a higher ecological condition, even if it is necessary, due to its high importance and sensitivity.

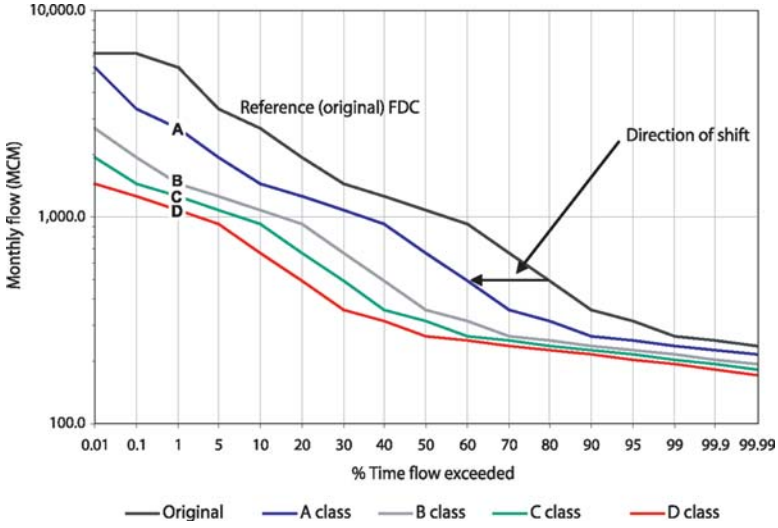
As this is the first time that such an approach is introduced in India, the focus should be on highlighting only the main aquatic features and problems of each basin. Such studies for several river basins, namely Cauvery, Krishna, Narmada, Periyar and Ganges have been initiated as part of this project. Aquatic ecology specialists from several Indian research organizations have been engaged in this research aiming to answer the above questions using several aggregate basin indicators, such as unique biota, aquatic habitat richness, aquatic species diversity, measures of flow regulation and catchment fragmentation, presence of protected areas, etc. The results are being summarized at the time of writing this report and will be presented in a separate publication. The default EMCs described in table 3 have been used in the current report as scenarios of aquatic ecosystem condition.

Establishing Environmental Flow Duration Curves

A simple approach is proposed to determine the default FDC representing a summary of EF for each EMC. These curves are determined by the lateral shift of the original reference FDC – to the left, along the probability axis. The mentioned 17 percentage points on the probability axis: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent are used as steps in this shifting procedure. A FDC shift by one step means that a flow which was exceeded, 99.99 % of the time in the original FDC will now be exceeded 99.9 % of the time, the flow at 99.9 % becomes the flow at 99 %, the flow at 99 % becomes the flow at 95 %, etc. The procedure is graphically illustrated in figure 2. A linear extrapolation is used to define the ‘new low flows’ at the lower tail of a shifted curve. The entire shifting procedure can be easily accomplished in a spreadsheet.

The difference between the default shifts of the reference FDC for different environmental classes is set to be one percentage point. In other words, a minimum lateral shift of one step (a distance between two adjacent percentage points in the FDC table) is used. This means that for a class A river the default environmental FDC is determined by the original reference FDC shifted one step to the left along the probability axis. For a class B river the default environmental FDC is determined by the original reference FDC shifted

Figure 2. Estimation of environmental FDCs for different Environmental Management Classes by lateral shift.



two steps to the left along the probability axis from its original position, etc. Any shift of a FDC to the left means several things:

- the general pattern of flow variability is preserved although with every shift, part of variability is 'lost';
- this loss is due to the reduced assurance of monthly flows, i.e., the same flow will be occurring less frequently; and
- the total amount of EF (i.e., EWR), expressed as 'environmental' MAR is reduced.

The method achieves the requirements of simplicity, match with flow data availability, maintenance of flow variability in the estimated environmentally acceptable flow regime and accommodation of different levels of environmental protection in the process. At the same time, it implies that environmental water demand would always be 'smaller' than a reference flow regime in both overall flow volume and flow variability terms. However, in cases of inter-basin water transfers, the EWR may need to be 'capped'. To establish such 'capping' EF at a site, a FDC has to be shifted to the right of its original position and certain degrees of shifting will need to be established for different classes.

Simulating Continuous Monthly Time Series of Environmental Flows

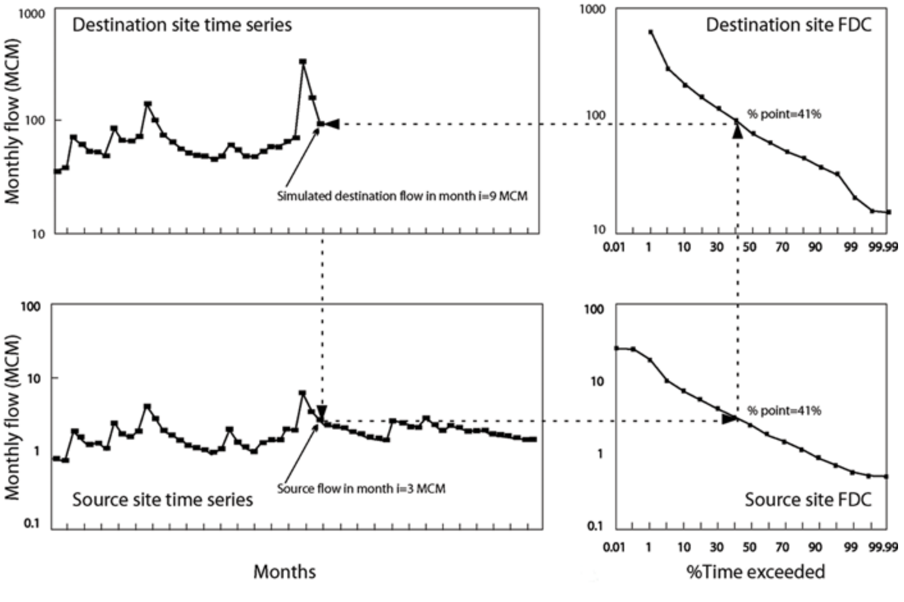
An environmental FDC for any EMC only gives a summary of the EF regime acceptable for this EMC. This summary is useful in its own right and can be used, for example, in reservoir yield analysis. The curve however does not reflect the actual flow sequence. At the same time, once such environmental FDC is determined as described above, it is also possible to convert it into the actual environmental monthly flow time series. The spatial interpolation procedure described in detail by Hughes and Smakhtin (1996) can be used for this purpose. The underlying principle in this technique is that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs.

The site at which streamflow time series is generated is called a *destination site*. The site with available time series, which is used for generation, is called a *source site*. In essence, the procedure is to transfer the streamflow time series from the location where the data are available to the destination site. In the context of this study, the destination FDC is the one representing the EF sequence to be generated, while the source FDC and time series are those representing the reference natural flow regime.

For each month, the procedure: (i) identifies the percentage point position of the source site's streamflow on the source site's period-of-record FDC, and (ii) reads off the monthly flow value for the equivalent percentage point from the destination site's FDC (Figure 3). More details about this procedure can be found in Hughes and Smakhtin (1996). Smakhtin (2000) suggested a method of calculating daily FDC from monthly FDC. If similar relationships are established for India, the EF regimes could be calculated similarly with a daily time step.

The generation of EF time series completes the desktop EF estimation for a site. The output is therefore presented in two forms – an *environmental FDC and a corresponding environmental monthly flow time series*. Such outputs should be suitable for interpretation and use by different specialists – those, like aquatic ecologists, who are more used to time series display and those, like civil engineers, who may be interested in aspects of assurance and incorporation of FDC into water resources system yield analysis.

Figure 3. The Illustration of the spatial interpolation procedure to generate a complete monthly time series of EF from the established environmental FDC.



Results and Discussion

Table 4 summarizes the results of EWR estimation at the outlets of several river basins and figures 4 to 6 show the duration curves of EF at these outlets. The estimates presented in table 4 have to be viewed in combination with the figures 4-6. One characteristic feature of the estimated EWR is that higher the flow variability of a river (and therefore the more steep the FDC slope is), the less the EWR are in all classes. Brahmaputra and Ganga, which have the least variable regimes according to simulated flow records and corresponding duration curves, have therefore the highest EWR. Rivers with the most variable flow regimes (and corresponding steeply sloping curves) like Mahi or Sabarmati have the lowest EWR in most of the classes.

Another noticeable feature is that the EWR in all classes for most of the rivers are relatively low compared with the environmental management objective and description of each class. For example, to maintain a river in a relatively high management class B, only 24 to 37 % of the natural MAR would be required, according to Table 4, with an exception of ‘extreme cases’ like Mahi, Brahmaputra and Ganga. The EWR for class D, which is sometimes perceived as the least acceptable, range only within 6.6 to 12.1 % of the natural MAR for different rivers, with exception of the same three rivers.

Table 4. Estimates of long-term EWR volumes (expressed as % of natural Mean Annual Runoff - MAR) at river basin outlets for different Environmental Management Classes obtained using FDC shifting method.

River	Natural MAR (BCM)*	Present day MAR (BCM *(% natural MAR))***	Long-term EWR (% *natural* MAR)					
			Class A	Class B	Class C	Class D	Class E	Class F
Brahmaputra	585		78.2	60.2	45.7	34.7	26.5	20.7
Cauvery	21.4	7.75 *(36.2)*	61.5	35.7	19.6	10.6	5.8	3.2
Ganga	525		67.6	44.2	28.9	20.0	14.9	12.1
Godavari	110	105 *(95.4)*	58.8	32.2	16.1	7.4	3.6	2.0
Krishna	78.1	21.5 *(27.5)*	62.5	35.7	18.3	8.4	3.5	1.5
Mahanadi	66.9		61.3	34.8	18.5	9.7	5.6	3.6
Mahi	11.0		41.9	17.1	6.5	2.3	0.8	0.3
Narmada	45.6	38.6 *(84.6)*	55.5	28.8	14.0	7.1	3.9	2.5
Pennar	6.3		52.7	27.9	14.3	7.3	3.8	2.0
Tapi	14.9	6.5 *(43.6)*	53.2	29.9	16.6	9.0	4.9	2.6
Periyar	5.1		62.9	37.3	21.2	12.1	6.9	3.9
Sabarmati	3.8		49.6	24.2	12.1	6.6	3.7	2.1
Subarnarekha	12.4		55.0	29.9	15.4	7.4	3.4	1.5

Notes: * Taken from table 1, with an exception for Periyar, where natural MAR was calculated directly from the observed flow record at Planchotte (1967-1979).

** Present day MAR is given only for rivers for which recent observed records at sites close to outlets were available (see table 2).

BCM = Billion Cubic Meters

Figure 4. Environmental Flow Duration Curves for Brahmaputra, Cauvery, Ganga and Godavari rivers.

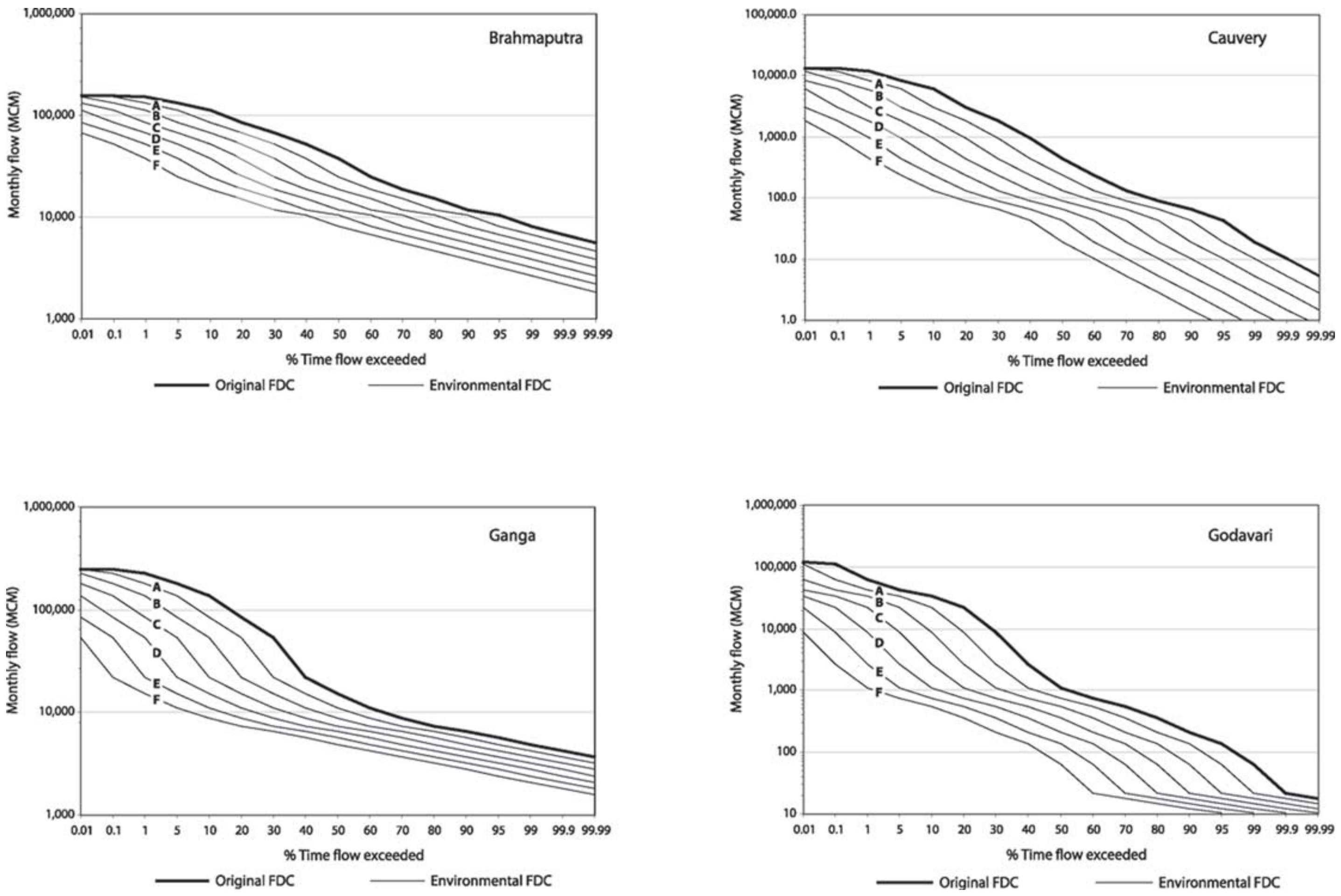


Figure 5. Environmental Flow Duration Curves for Krishna, Mahanadi, Mahi and Narmada rivers.

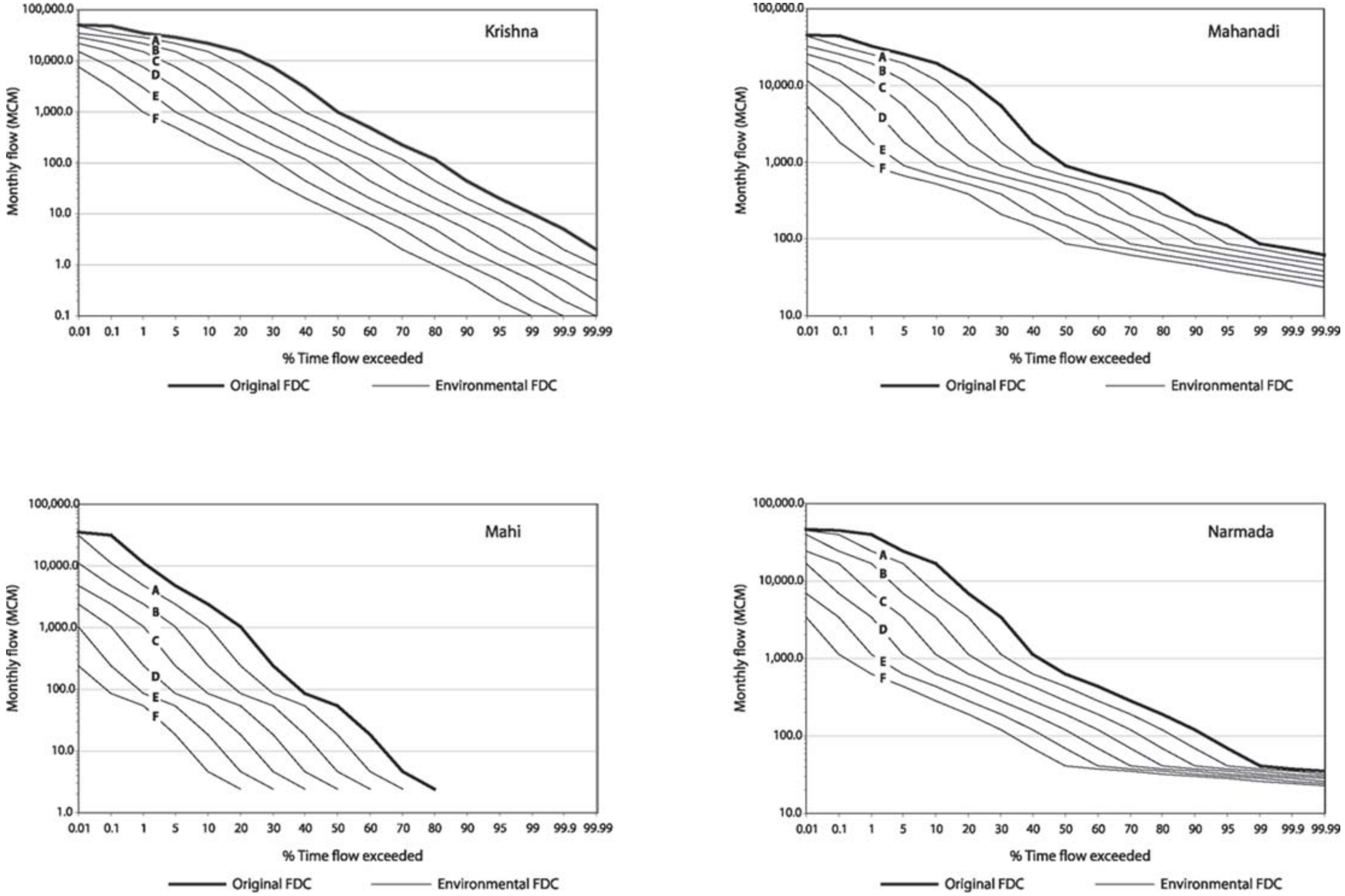
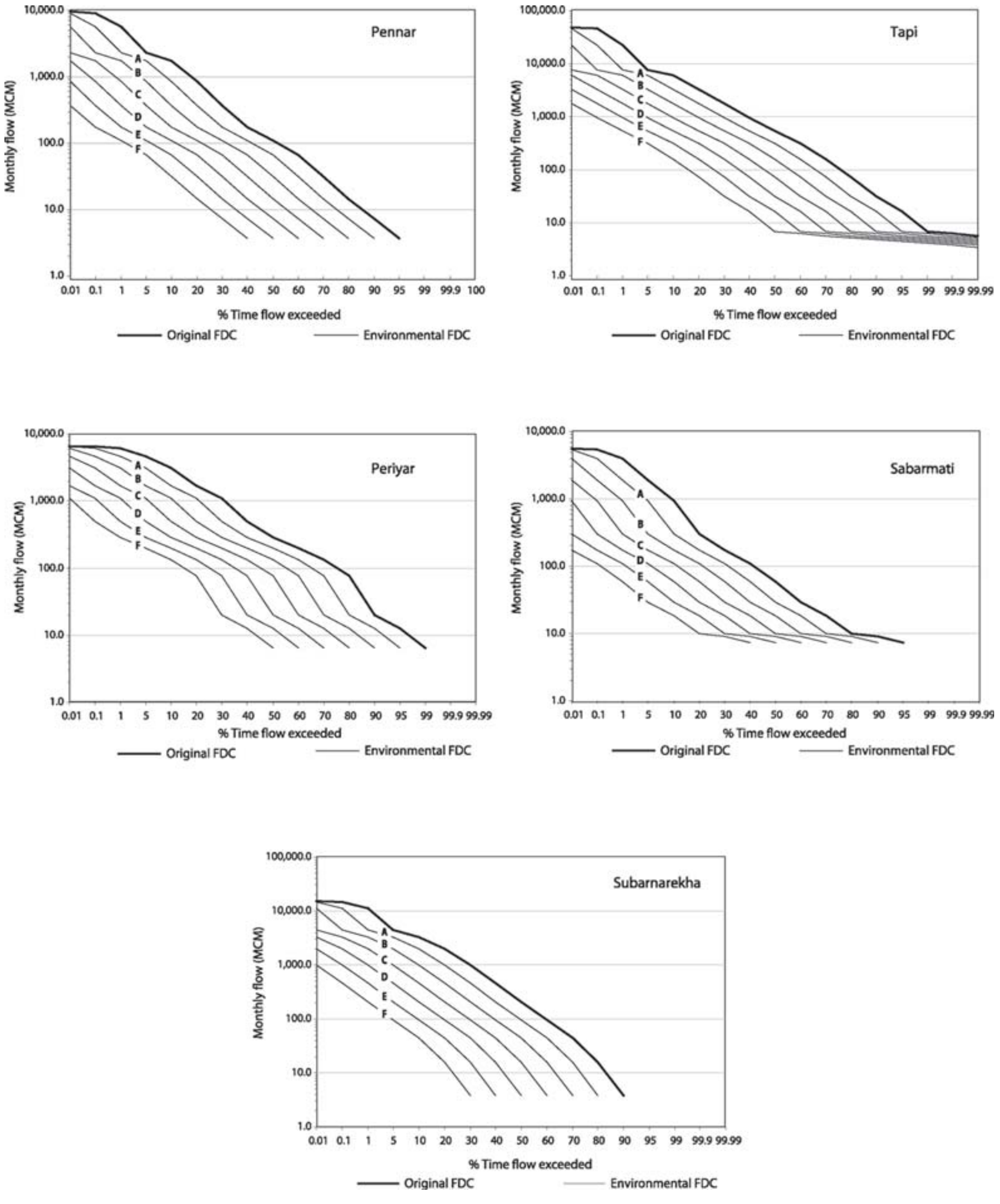


Figure 6. Environmental Flow Duration Curves for Pennar, Tapi, Periyar, Sabarmati and Subarnarekha rivers.



The main methodological issue is the justification of currently used magnitudes of lateral FDC shifts per EMC. The step of a FDC shift currently used has been inferred partially from literature sources and partially through limited 'calibration' against the EF estimates obtained by DRM. Australian experience suggests that "the probability of having a healthy river falls from high to moderate when the hydrological regime is less then two-thirds of the natural" (Jones 2002). Despite the general vagueness of this statement, it could indicate that the EWR of some 60-70 % of natural MAR are likely to be required for the maintenance of rivers in A and B classes. By progressively shifting the curves for different rivers one step at a time and calculating corresponding EWR, it is possible to establish how many such shifts are generally permissible to ensure A and B class rivers. A FDC shift of one percentage point has been found to achieve the above flow reduction in most of the cases (Table 4). On the other hand, the already mentioned Tennant method suggests that the lowest feasible limit for the EWR, corresponding to severe degradation of a riverine ecosystem, is 10 % of the natural MAR. In most cases, this benchmark may be achieved or exceeded by four subsequent FDC shifts to the left along the probability axis (Table 4). This may then be interpreted as the EWR of a class D river.

Overall, the determination of the number of FDC shifts per EMC is difficult without knowing the relationships between ecological characteristics and flow modifications in rivers with different hydrological regimes. In the absence of such knowledge, we use the minimum possible lateral shift per EMC. This may be seen as a conservative 'pro-environmental' approach, as shifts by only one step per EMC minimize losses in flow volumes and variability allocated to an ecosystem. However, as shown in Table 4, even this limited shift step results in significant losses of flow volumes and variability per class.

It is possible that as a result of subsequent future research, the procedure will differ between more variable, mostly non-perennial rivers and less variable, mostly perennial rivers in terms of how much FDC shifts are permissible in different classes. For example, the resilience of aquatic ecosystems is usually the strongest when they are healthy (A and B class rivers). Therefore, larger FDC shifts – by two steps per EMC - and, consequently, larger corresponding flow reductions could be assumed acceptable to derive the default estimates of EWR for 'more natural' classes A and B. Accordingly, smaller FDC shifts (by one step per EMC) could be accepted to derive the default estimates of EWR for moderately to significantly modified ecosystems described by classes C to F.

It is important to stress that the shift limits assumed above for each class are *the defaults*. Furthermore, variable shifts for different percentile flows can be used, if there is a specific justification for this. For example, while estimating environmental FDC for A and B classes, flows exceeded 90, 95 % and more of the time in the reference FDC may need to be fixed at their 'existing positions'; other flows may be shifted as in the default case. Alternatively, various shifts could be used for different percentile flows to define an EF duration curve in any EMC. The same logic can be taken even further. Fixed EMCs may become unnecessary if a limited set of ecologically important flows is identified and permissible shifts in each (determined by the panel of experts for example) will jointly describe the final prescribed/negotiated state of the river. It should be possible to establish better shifting procedure and more justified levels of shift through one or several national specialist workshops involving local hydrologists and ecologists. The proposed approach therefore can provide the basis for further technique development.

The EWR estimates obtained using the FDC shifting technique may also be interpreted in the context of the EWR estimates produced by the Desktop Reserve Model (DRM), described in the Review section (see section: *Review of Environmental Flow Assessment Methods).* Comparing EWR obtained by both DRM and FDC shifting methods should be seen as a form of calibration of the latter. The rational for this is that the DRM is effectively based on the results of more comprehensive and higher-confidence EFA, which, in turn, are based on Building Block methodology with a good 'track record'. Comparing the estimates obtained by two methods is effectively the only possible form of testing the proposed shifting technique at present, since no EF estimates are available in India. It should be noted that the DRM parameters have been regionalized for South Africa only. While it is obviously necessary to modify DRM parameter values for Indian conditions, currently there are no scientific grounds upon which to base any such changes. Direct DRM application for Indian rivers, where there is no specialist science input from ecologists, geomorphologists, etc., is therefore expected to produce highly uncertain EWR estimates.

The DRM-estimated EWR values for sites, where observed and unregulated records were available are listed in Table 5. Similar to the FDC shifting method, the class A results for Ganga and Brahmaputra are unrealistically high and further attention needs to be given to both. Also, the most variable rivers like Mahi, Sabarmati, etc., have the lowest EWR. At the same time, the DRM estimates appear to be consistently more conservative than the FDC shifting method for 'lower' classes, where DRM produces higher EWR (Figure 7). For example, almost all class D EWR requirements calculated by DRM are approximately double that of the FDC shifting method (Figure 7). The higher EWR in lower classes calculated by the DRM may however simply be the reflection of parameter uncertainty mentioned above. Much less difference is present between the EWR estimates produced by both methods for class C, where some of the Indian rivers may still be placed (despite the fact that some, like Narmada, are also heavily committed to future developments). Because classes E and F are not considered acceptable in DRM, they are not included in Table 5.

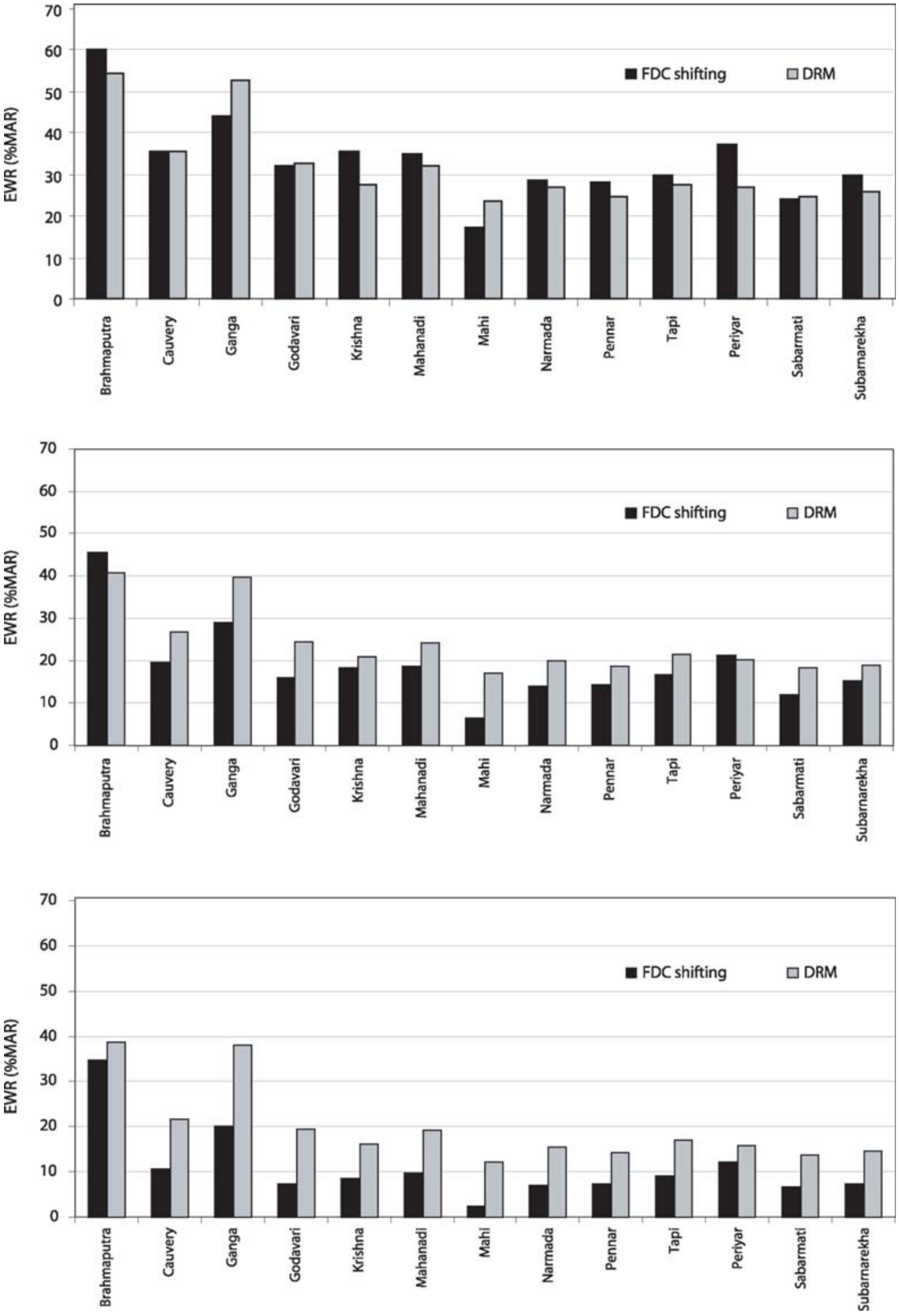
The suggested prototype EFA method is based on *monthly* flow time series. Therefore, the reduction in flow magnitude due to lateral shift of a FDC does not necessarily mean that *daily* flows will be reduced accordingly. It may, however, mean that, for example, the number of high flow events in the wettest months may be allowed to drop, thus leading to the overall

Table 5. Estimates of long-term EWR volumes (expressed as % of MAR) for selected river basins and different Environmental Management Classes obtained using Desktop Reserve Model.

River and Site	MAR (BCM)	Hydrological Variability Index	Long-term EWR (% MAR)			
			A	B	C	D
Brahmaputra @ Pandu	573.8	1.0	85.4	54.5	40.6	38.6
Cauvery @ Krishnaraj Sagar	5.37	3.4	50.8	35.8	26.7	21.7
Ganga @ Farakka	380.0	1.0	82.4	52.9	39.7	38.1
Godavari @ Davlaishwaram	96.6	4.7	45.4	32.7	24.5	19.6
Krishna @ Vijayawada	56.7	5.8	38.4	27.8	20.8	16.1
Mahanadi @ H. K. Sambalpur	54.8	5.1	44.7	32.0	24.1	19.2
Mahi @ Sevalia	12.2	13.7	32.7	23.3	16.9	12.3
Narmada @ Garudeshwar	22.6	5.4	37.3	26.8	20.0	15.5
Pennar @ Nellore	2.34	7.7	33.3	24.7	18.7	14.3
Tapi @ Kathore/Ghal	4.50	6.7	36.9	27.6	21.4	17.0
Periyar @ Planchotte	5.15	4.6	38.1	27.1	20.1	15.7
Sabarmati @ Ahmedabad	1.04	8.6	34.1	24.7	18.2	13.6
Subarnarekha @ Kokpara	9.76	8.1	35.3	25.6	19.0	14.6

Note: BCM = Billion Cubic Meters

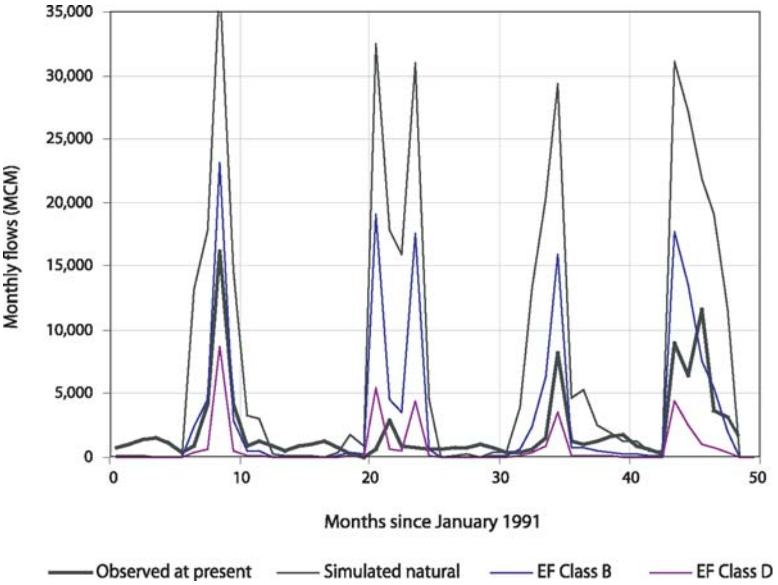
Figure 7. Comparison of Environmental Water Requirements estimated by FDC shifting method and DRM for EMC B (top), C (middle) and D (bottom).



decrease in monthly flow volume. Some comprehensive EFA methods (e.g., DRIFT, King et al. 2003) consider possible scenarios of flow changes in terms of how many events of certain magnitude can be allowed to be "lost" (e.g., can all dry season freshes be lost, or can the number of floods occurring at least once a wet month be halved). Reduction in corresponding monthly flows, which results from the FDC shifting, effectively reflects these daily flow scenarios.

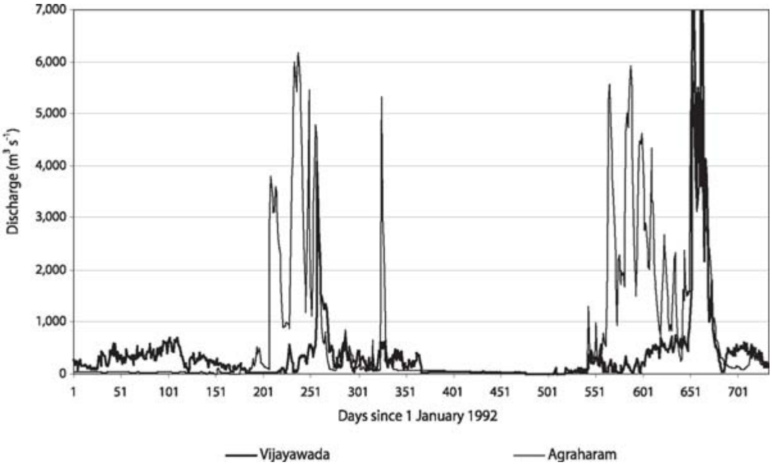
The estimated EF should be interpreted in the context of natural and present day river flows. This could show what level of environmental protection is achievable in principle, given the current extent of water resources development. Figure 8 illustrates the present-day flow conditions at Krishna at Vijayawada town – the closest to the outlet - in the context of naturalized (simulated) flow at the outlet and the simulated EF time series for EMCs B and D. The simulated time series were obtained using the spatial interpolation procedure discussed in the previous section and illustrated in Figure 3. Figure 8 shows that despite the seemingly high present-day 'observed' MAR (28% of the natural MAR) monthly flows at the outlet in certain years drop to the level of the EF corresponding to class D, which is the least acceptable.

Figure 8. Extracts from observed and simulated monthly flow hydrographs for Krishna at Vijayawada.



Low flows during the non-monsoon period normally exceed the simulated 'natural' low flows (Figure 8). This may be due to irrigation return flows or be the result of flow regulation. Figure 9 illustrates this point further by showing extracts from two observed daily flow time series in Krishna. The first time series is from the upstream site of Agraharam town located on the main stream of Krishna. This site commands the catchment area of 132,920 km^2. The second site is located at Vijayawada and commands almost the entire basin area of Krishna (251,360 km^2). The Agraharam site is located upstream of all major dams on Krishna's main channel and may reflect unregulated daily flow conditions. The flow at Vijayawada, on the other hand, is severely impacted by flow regulation from dams located downstream of Agraharam. This

Figure 9. Observed daily hydrographs in Krishna at Agraharam (upstream station, catchment area 132,920 km^2) and Vijayawada (basin outlet, catchment area 251,360 km^2).



regulation effectively removed all major high flow events from the river, increased low flows and distorted their pattern, shifting seasonal flow distribution and completely changing the inflow pattern to ecologically sensitive delta area.

Conclusions and the Way Forward

This study attempted, for the first time, to consistently review the trends and philosophy of EFA in India and to apply the concepts of desktop EFA to Indian rivers. The main purpose of the study is to stimulate the emerging debate on EF and environmental water allocation prospects in the country. The results suggest that river ecosystems may, in principle, be maintained in a reasonable state even with the limited EF allocations (10-20% of natural MAR depending on hydrological variability). Because of severe data limitations, the magnitude of the task and the very coarse scale of the analysis (the entire large river basins only), *the results presented herein should be viewed as illustrative*. At the same time, the prototype desktop EFA method suggested in this study has a number of advantages:

- It is commensurate with existing data and understanding of eco-hydrological relationships, simple and quick to apply and explicitly includes the concepts of hydrological variability, which as the modern hydro-ecological theories agree, caters for the requirement of various ecosystem components.
- It can present the environmental water demand in terms of both – the cumulative measure (EF duration curve) and the actual time series of EF regime. The first reflects the overall pattern of EF variability whereas the second shows the actual sequence of flows in environmentally acceptable flow regime.
- It is generic and can be applied to catchments of any size and in any physiographic conditions.

- It can and should be made more flexible by applying different shifts at different percentile flows and examining the results on the output EF time series. It is therefore important to stress that the method suggested should rather be seen as a step towards a better justified desktop EFA tool in the future.

The main issue with the method at present is a limited justification of the permissible FDC shifts per EMC. The currently accepted step of a shift (one FDC table point per class) is based on limited calibration of the proposed method against a more advanced DRM technique, which however has also not been adjusted for use in Indian conditions and therefore produce uncertain EF estimates itself. It is very difficult to evaluate the results when there are no ecological data available to confirm or deny the suitability of the estimated EF. It is, in principle, possible to collect some limited hydraulic information for rivers and examine the characteristics of the available habitat (water depth, wetted area and velocity, for example) under different flow conditions (natural and FDC shifting method recommendations). This is not, however, a real substitute for scientific information on the relationships between ecological characteristics and flow. It is also recognized that the collection of such information will be very time consuming and expensive.

For rivers with less variable flow regimes (and hence gently sloping FDCs), the technique may reduce high flows significantly more than low flows. However, first, at the monthly time step, this does not necessarily imply the reduction of daily peaks; it could be the number of high–flow events which is reduced. Second, from a management perspective this may not be a major issue. Unless major storage dams exist with substantial high flow release facilities, the high flows may not be controlled. The management focus therefore should be on the low flows, while the assumption can be made that high flows will occur, more-or-less naturally.

For the long-term, the focus of the future EFA in India has to be on the quantification of eco-hydrological relationships in rivers and on inventory of already existing ecologically relevant information. It is necessary to consider initiating several comprehensive EFA projects in different parts of the country and to relate the results to hydrology of the basins. This would also help to better justify and improve the FDC shifting method suggested here.

It is logical to initiate such projects at several sites which will be affected by the planned NRLP inter-basin water transfers. Immediate EFA of some ‘signed’ off links has to be done – like those between Ken River and Betwa River, on which the agreement has been signed by Madhya Pradesh and Uttar Pradesh governments in August 2005. Such detailed EFA studies will effectively initiate a long-term capacity building programme in this field in the country by engaging ecologists and hydrologists who know their local rivers. Even if they have limited information required for such assessment and the results are therefore still uncertain, attempting a detailed EFA develops team building and interactions between experts in different disciplines.

At the same time, simple EFA tools, such as the one suggested in this report, may help to illustrate the type of expected outcome from a more comprehensive EFA. Simple tools do not exclude, but rather encourage capacity building and the use of comprehensive EFA methods at the same time. One possible merge of the two approaches (complex and simple) could be through a workshop of Indian ecologists and hydrologists, which could discuss and/or define the required shifts of FDCs for different EMCs.

Eventually, a set of EFA tools will need to be developed and tested in a specific context of India’s flow regimes, ecology and water resources development. The types of EFA methods have to be selected based on the type of proposed development (abstractions, in-stream or off-channel reservoirs, flow reduction activities, etc.), the level of impact of the proposed development, the ecological importance and sensitivity of the river, the degree to which it is already developed, the socio-economic importance of the river and its proposed development, etc. The more critical the proposed development is from the above issues, the more likely that more comprehensive EFA will need to be used.

It is also necessary to initiate an assessment of ecological importance and sensitivity and ecological conditions of all major river basins in India and with the detailed spatial resolution. The information provided through such assessment is also useful in its own right – outside of the context of EF, because it gives the idea of the ecological condition and importance of aquatic ecosystems (albeit in a semi-quantitative way) and therefore contributes to the vision of India's water future.

The study has effectively not been supplied with observed flow data of reasonable amounts and quality. The data which have been acquired and used were primarily from publicly available sources (Internet) where data are outdated and no conclusions on the accuracy or even origin of the data could be made. If the situation with access to data in India is not changed, any further EFA will be largely speculative. On the other hand, the agencies responsible for hydrological data provision will increasingly realize that the recent advances in global hydrological modeling and remotely sensed data acquisition have been so significant that in the near future (5-10 years) lack of access to observed data may no longer be an obstacle, because the representative and reliable flow time series for any site at any river could be simulated and be more reliable than observed.

One issue, which has not been addressed in this report, is how EF relates to the water quality of rivers. This is an even more complex issue than EF estimation itself, but a few statements can be made to that effect. First, EF should aim to achieve some ecological objective (e.g., provide flow-related habitat or geomorphological function), but not to solve river water quality problems by dilution. At the same time, once EF are recommended and expressed as a time series/duration curve, it should be possible to simulate flow-concentration relationships for important constituents. Through this, the anticipated water quality consequences of modified flows could be explored and examined in the context of some pre-defined water quality classes (Palmer et al. 2005). The latter could be established using some benchmarks - literature or field-data based boundary values. If recommended EF does not allow the agreed water quality targets to be met (e.g., in cases when a river has naturally high salinity and recommended environmental low flows would lead to increased salinity beyond some critical levels) then higher EF should be considered. *Severely polluted Indian rivers are at risk only if the recommended EF remain in the river without non-point source pollution control and without effluent treatment at source.*

Last but not the least is the issue of actual *EF provisions* as opposed to *EF assessment*. No matter how advanced and accurate the EFA is, its output remains on paper if no actual releases are made or if the prescribed limit of water resource exploitation is violated. There are very few examples in the world when environmental water requirement are actually satisfied by EF provisions. Similarly, this may be the major stumbling block on the way to environmentally sustainable water resources development in India. Therefore, a due consideration to relevant policy support and enforcement has to be given to it.

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Developing Procedures for Assessment of Ecological Status of Indian River Basins in the Context of Environmental Water Requirements

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Introduction

Environmental water requirements, also referred to as 'Environmental Flows' (Dyson et al. 2003; Acreman and Dunbar 2004), are a compromise between water resources development and the maintenance of a river in some ecologically acceptable or agreed condition. The issue of environmental flows is relatively new in the world. Existing environmental flow assessment methods reflect the diversity of opinions on this subject and range from comprehensive expert panel approach to arbitrarily selected hydrological indices (e.g., Tharme 2003). In many developing countries, such as India, the issues of environmental water demand have not yet received the required attention. The first National Workshop on Environmental Flows, held in New Delhi, in March 2005, brought together over 60 participants from national agencies and research institutions. The workshop generated a significant interest on the concept of environmental flows in the country, and it also revealed the existing confusion in this field. Smakhtin and Anputhas (2006), attempted to further stimulate the debate on environmental water demand in India by suggesting a simple desktop assessment method and using it in several major river basins. The method, however, was designed in conditions with very limited hydrological, and no ecological, data. One of the major problems with developing environmental flow work in countries like India, is that despite existing significant knowledge on some aquatic ecosystem components (e.g., fish), it has never been interpreted in the context of environmental flow assessments. This means that it is not, as a rule, known how different ecosystem components in different biogeographical settings react to changes of flow caused by water resources or land developments. The impacts of reducing/increasing high or low flows on fish, invertebrates, riparian vegetation, or sediment regime (which is one determinant of aquatic habitat), for example, are not quantified. In some countries, the lack of such relationships and quantitative knowledge is addressed by expert panels and/or by certain scoring systems, which rank a condition of an ecosystem and/or its sensitivity to flow changes (Cottingham et al. 2002; DWAF 1999; Rogers and Bestbier 1997). Such scores are then fed into the determination of an environmental category or environmental management class (EMC). EMC, in turn, is used (together with measures of flow variability or analysis of hydrological time series) to determine the acceptable limits of flow reduction/increase in a river, i.e., actual environmental flows. It is assumed that the higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation and, more flow variability will need to be preserved. The existing scoring systems reflect the level of available expertise and ecological data. This report attempts, for the first time, to introduce a prototype scoring system for the ecological status of rivers in India and illustrates the same through its application in several major river basins. The attempt has been significantly inspired by the South African experience. However, it is a major simplification of the existing practice. It is presented here as an attempt to show one possible protocol for placing a river into a certain environmental management class, rather than to prescribe it for use in its current form.

Methodology

Ideally, the definition of the environmental management class (EMC) should be based on existing empirical relationships between flow changes and ecological status/conditions, which are associated with clearly identifiable thresholds. Despite some documented examples, limited evidence or knowledge is available of such thresholds (e.g., Beecher 1990; Puckridge et al. 1998). Therefore, EMC is a management concept that has been developed and used in the world because of a need to make decisions regardless of the limited lucid hydro-ecological knowledge available. In these conditions of uncertainty with regard to which EMC is required for a particular river, the EMCs may be used as default ‘scenarios’ of environmental protection and associated environmental flows—as ‘scenarios’ of environmental water demand (Smakhtin and Anputhas 2006). It is possible to estimate environmental demand corresponding to all or any of such default EMCs and then consider which one is the most feasible for a river in question, given the existing and future basin developments. Alternatively, it is also possible to use expert judgment in order to place a river into the most ‘achievable’ EMC. One can think of an ‘ecological water passport’ for a basin. Such a ‘passport’ could include answers to the following three, broad questions:

- *What is the ecological sensitivity and importance of a river basin?* The rationale for this is that the higher the ecological sensitivity and importance of aquatic ecosystems in a river basin is, the higher the EMC should be, ideally.
- *What is the current condition of aquatic ecosystems in a river basin?* The more natural the current condition of the basin is, the greater the incentive for its maintenance as such.
- *What is the trajectory of change?* This question aims to identify whether a river is still changing, and in what direction, how fast and due to what impacts. The rationale is that if the deterioration of aquatic environment continues, it will be more difficult to achieve a higher EMC, even if it is necessary, due to its high importance and sensitivity.

As this is the first time that such an approach is introduced in India, the focus should be on highlighting the *main* aquatic features and problems of each basin. This means that *aggregate environmental indicators*, which reflect different features or conditions of a river basin, could be used for scoring. The literature on environmental indicators is fairly extensive and its comprehensive review is beyond the scope of this report. Some of the relevant recent works include, for example, Galbraith (2001), who developed a set of indicators that could be used to assess the condition and coping capacity of freshwater ecosystems at the basin scale. These indicators include: percentage of the basin under natural vegetation; percentage of the floodplain under agricultural and urban land use; percentage of the lakes in eutrophic state; and several others. A similar indicator approach has been widely used in large-scale international water assessment programs such as Global International Waters Assessment (GIWA, http://www.giwa.net), Watersheds of the World (Revenga et al. 1998) or Land-Ocean Interactions in the Coastal Zone (LOICZ, http://www.loicz.org). However, the aggregate environmental indicators have never been previously used in the context of environmental flow assessment.

The first question above may be seen as an attempt to design a condensed measure of the ecological value of the basin, albeit in non-monetary terms. An arbitrarily selected set of semi-quantitative and quantitative indicators includes:

- Presence of rare and endangered aquatic biota
- Presence of unique (e.g., ‘endemic’) aquatic biota
- Diversity of aquatic habitats
- Presence of protected areas, areas of natural heritage and pristine areas, which are crossed by the main water course in the basin
- Sensitivity of aquatic ecosystems to flow reduction

Indicators from this group are calculated using national ecological surveys and databases. Considering that most of the ‘ecological’ attention in countries like India has so far been given to fish, such indicators as *rare and endangered biota and unique biota* are calculated here using available fish data. Rare and endangered fish species are first identified using IUCN (1994) categories such as CR (critically endangered) and EN (endangered). Their cumulative number is then expressed as the proportion of the total number of fish species found in a river basin. The assessment of *diversity of aquatic habitats* and s*ensitivity of aquatic ecosystems to flow reduction* requires expert judgment and knowledge of a particular river. *Presence of protected or pristine areas* can be assessed against existing guidelines for protected area management, i.e., IUCN (1980), which sets the aim of 10 % of the basin to be protected.

The second question above relates to what the river system looks like at present, compared to a reference condition in the past (e.g., prior to construction of major dams), or compared to some similar and relatively undisturbed subbasins in the same physiographic settings. The indicators used in this study include:

- percentage of the watershed remaining under natural vegetation cover types
- percentage of the floodplain areas remaining under natural cover types
- percentage of aquatic biota that are exotics

- overall richness of aquatic species
- the degree of flow regulation
- the degree of river fragmentation
- human population density in a river basin (percentage of population density in the main floodplains)
- overall water quality in the basin

The first two indicators are normally estimated from the GIS maps, remote sensing data, or already published literature sources. In some cases, a percentage of the floodplain areas actually remaining in a basin compared to some past reference condition may be used as an alternative to the second indicator. A *proportion of exotic species* (e.g., fish), can be calculated as a percentage of the number of total fish species recorded in the basin. *Overall species richness* may be assessed as a proportion of the total number of species in a country, or in a larger geographical region, whichever is more appropriate, or by an expert score on a scale from low to high. The most straightforward way of calculating the *degree of flow regulation* is as a ratio of total storage of all dams to the long-term mean annual natural flow volume of the basin. It is acknowledged though that this approach does not recognize timing or types of flow events that are altered—which may be more critical than change in volume *per se*. *A degree of river fragmentation* can be represented by a simple indicator of spatial changes to habitat—longitudinal and latitudinal (river-floodplain) connectivity of rivers. *Human population density in a river basin as a percentage of population density in the main floodplains* (which could be seen as an aggregate indicator of human pressure on aquatic ecosystems) may be calculated using Census data and GIS, where the floodplains are arbitrarily defined as areas within 2.5 kilometers (km) of either side of the main channel and the channels of the main tributaries (e.g., Revenga et al. 1998). (It is acknowledged that such a definition does not fully recognize the difference between the typical riparian zone and floodplains). An approximation of the overall water quality in a river is indexed using Indian national water quality categorization, which has several classes, from A to E — depending on the level of pollution—expressed by ranges of several constituents.

With regard to the *third question above*, no specific indicators are used and ‘trend assessment’ is left primarily to professional judgment. It may be seen as an attempt to foresee how the river will look like in the short-term (e.g., 5 years) and in the long-term (e.g., 20 years) in case of a ‘do-nothing-to-protect-aquatic-environment’ scenario.

Regardless of the original units and ways of estimation of every individual indicator, all indicator values in this study are then converted to a standard scoring system, which includes ratings: 1 (none), 2 (minor), 3 (moderate), 4 (high) and 5 (very high). Table 1 summarizes the indicators which have been used in this study, and explains why an indicator has been considered and how it is relevant in the context of the estimation of environmental water demand. The scores for individual indicators are then summed up and their sum is expressed as a percentage of the maximum achievable score. The actual percentage shows the degree of the deviation of a basin from its natural condition and, therefore, the most probable EMC. The latter, in turn, may be related to the amount of water that needs to be allocated for environmental purposes in this basin.

Table 1. A preliminary set of basin indicators, their scoring systems and justification.

Indicator	Range	Score	Justification in the Context of Environmental Flow Assessment
Indicators Related to Ecological Value (Importance and Sensitivity)			
Rare and endangered aquatic biota	Very High High Moderate Minor None	5 4 3 2 1	The total number of rare and endangered species can be expressed as a percentage of the total number of species in a country, region or basin—depending on the scale of analysis. These percentages may be related to the range and to the score. The more rare and endangered aquatic biota is present in the basin, the more sensitive the rivers generally are to flow changes (e.g., to reduction). Consequently the more effort is needed to maintain the flow in a river at least at existing levels.
Unique aquatic biota	Very High High Moderate Minor None	5 4 3 2 1	The number of unique (endemic) species can be expressed as a percentage of the total number of species in a country, region or basin—depending on the scale of analysis. These percentages may be related to the range and to the score. The assumption is that the more unique aquatic biota is present in the basin, the more important it is to ensure that they do not get affected by flow modifications. Therefore, more flow and more flow variability needs to be preserved in a river.
Diversity of aquatic habitats	Very High High Moderate Minor None	5 4 3 2 1	Can be estimated either by professional judgment or a more quantitative approach, e.g., by identifying different habitat types in representative river reaches and then calculating the representative value for a basin. Example of habitats include runs (rapidly flowing water with a gradient over 4% with no surface turbulence), pools, glides (a shallow stream reach with a maximum depth of under 5% of the average, and without surface turbulence), pocket water (one or a series of small pools in a section of flowing water containing numerous obstructions), backwater (abandoned channel that remains connected to the active main river or secondary channel in which the inlet is blocked with deposition at low water velocities but the outlet remains connected with the active main channel), floodplains and marshes (including mangroves), etc. The assumption is that the more habitat types are present, the more incentives should exist to preserve them to ensure the aquatic biodiversity as well.
Presence of protected areas of natural heritage and pristine areas which are crossed by the main watercourse in the basin	>10 5–10% 3–5% 1–3% <1%	5 4 3 2 1	Based on the IUCN aim of 10% of the basin area to be protected. The more area that is protected, pristine or 'a must to be preserved,' the more flow is likely to be necessary to be left in rivers, or to be released into them for maintenance of aquatic life.
Sensitivity of aquatic ecosystems to flow reduction	Very High High Moderate Minor None	5 4 3 2 1	Can be evaluated using professional judgment and knowledge of a river. A limited decrease in flow in some rivers may result in particular habitat types (e.g., floodplains, riffles, brackish costal wetlands, estuaries) becoming unsuitable for biota, compared to other rivers, e.g., smaller rivers versus larger rivers, rivers in drier areas versus those in more humid ones, etc. The assumption is that highly sensitive ecosystems need more water to maintain them in the current or desired condition.

(Continued)

Table 1. A preliminary set of basin indicators, their scoring systems and justification. (Continued)

Indicator	Range	Score	Justification in the Context of Environmental Flow Assessment
			Indicators Related to Ecological Condition of Aquatic Ecosystems in the Basin
Percentage of watershed remainin under natura vegetationg	70–100%	5	Can be estimated using RS images, from literature sources or based on field surveys. These are measures of the extent to which natural vegetation communities have persisted in a watershed or a floodplain. An area that retains a high proportion of natural cover types may be expected to also have many essential ecosystem services, such as flood control, still intact. Because it still Percentage of floodplain contains ‘natural capital’ in the form of natural communities, the ecological remaining under natural structures and functions of such a watershed or floodplain would also be vegetation cover types expected to be more more sustainable, and their resilience and ability to cope with anthropogenic and natural stress would be greater. The assumption is that the higher the values of both indicators, the more biodiversity is likely to be preserved and the more the basin is insured against the functional degradation. If the natural capital is important to maintain at existing conditions, the higher EMC will be necessary and more environmental flows will be required.
	50–70%	4	
	30–50%	3	
	10–30%	2	
	<10%	1	
cover types	70–100%	5	
	50–70%	4	
	30–50%	3	
	10–30%	2	
	<10%	1	
Degree of flow regulation	>100%	1	The first indicator is the total dam storage in a basin as a percentage of the mean flow, the second—the catchment area upstream of dams as a percentage of the total catchment area. These are important determinants of the habitat condition and aquatic biodiversity. Many riverine species move large distances through channel networks as part of their life history requirements. Dams and weirs disrupt longitudinal connectivity and fragment populations leading to decline in aquatic biodiversity. Migratory species often form the basis of productive fisheries and are typically the most affected by such barriers. A high density of impoundments prevents biota from migrating to preferred habitats such as upstream spawning beds. As these ecological processes are degraded, the sustainability and coping capacity of the system is reduced. Environmental flows should be allocated to cater for longitudinal and lateral connectivity. The more the river system is fragmented, the lower is the ecological status, hence a lower environmental management class is achievable.
	50–100%	2	
	20–50%	3	
	10–20%	4	
	0–10%	5	
Percentage of the watershed closed to movement of aquatic biota by anthropogenic structures	70–100%	1	
	50–70%	2	
	30–50%	3	
	10–30%	4	
	<10%	5	
Degree of flow fragmentation			This indicator is an alternative to the above one. The ranges are expressed in a number of structures per km of river length.
	0	5	Naturally flowing river without structures.
	0.001–0.01	4	* With/out upstream storage reservoirs and with possibilities of movement upstream—like fish ladders—for aquatic fauna.
	0.01–0.1	3	* With/out upstream storage reservoirs and with possibilities of movement upstream—like fish ladders—for aquatic fauna.
	0.1–1	2	* With/out storage reservoirs with/out possibility for movement upstream for aquatic fauna only during monsoon.
	>1	1	* With/out storage reservoirs with/out possibility for movement upstream for aquatic fauna only during monsoon.

(Continued)

Table 1. A preliminary set of basin indicators, their scoring systems and justification. (Continued)

Indicator	Range	Score	Justification in the Context of Environmental Flow Assessment
Indicators Related to Ecological Condition of Aquatic Ecosystems in the Basin			
Percentage aquatic biota that are exotics	0% <5% <10% <20% >20%	5 4 3 2 1	Successful invasion by exotic species often incurs losses and disruptions in ecosystem structures and functions (e.g., loss of biodiversity due to competitive exclusion and predation, disruption and modification of food webs, loss of habitat for fish and wildlife). Thus, the percentage of exotic species in a reach or a basin provides information on its likely sustainability and coping capacity. The higher the proportion of exotic species the lower the achievable EMC is.
Fish species relative richness, aquatic plant species relative richness, etc.	Very High High Moderate Minor None	5 4 3 2 1	These are measures of biodiversity remaining in a system and therefore—of its ecological capital and ability to self-organize and sustain itself and cope with stressors. It is important to address relative richness, rather than just speciescounts because the baseline biodiversity of an area is conditional on habitat types, geographical locations, etc. Thus, the number of species that inhabit a watershed should be expressed as a percentage of the number that would be expected to occur there in the absence of human interventions. Xenopoulos et al. (2005) have shown that fish species numbers are reducing with reducing discharge. The reference condition is, however, very often difficult to establish and consequently the quantification of ranges is also difficult. As a surrogate for the percentage of some 'natural' reference condition, the species richness may be quantified as a percentage of overall species in the country or geographical zone, or established by professional judgment.
Human population density in the entire river basin as a percentage of the population density in the main floodplains	<10% 10–20% 20–40% 40–60% >60%	1 2 3 4 5	Can be estimated using Census data. Districts located primarily in floodplain areas can be used to estimate population density in floodplains, other districts - to estimate population density in the rest of the basin. It is assumed that this measure may be seen as an aggregate indicator of human pressure on aquatic ecosystems and as an indicator of disruption of lateral connectivity in river basins.
Overall water quality in the basin	Class A Class B Class C Class D Class E	5 4 3 2 1	National Indian categorization of water quality is used, where each class is characterized by certain ranges of constituents. Water in Class A can be used for drinking after disinfection; water in class B is only for swimming and bathing; water in Class C requires conventional treatment and disinfection before drinking; water in Class D is suitable for propagation of wildlife and fisheries; and water in class E is only suitable for such uses as irrigation and industry cooling.

The Study Basins

The river basins which have been selected for this study include Krishna, Cauvery, Narmada, Periyar and part of Ganga. The selection has been based primarily on availability of expertise and data for each basin. The attempt, however, has been made to ensure the geographical spread of basins throughout the country, the range of catchment sizes, degrees of development and environmental issues. Most of the selected basins are earmarked for interbasin water transfers under the National River-Linking Project (NRLP).

The methods of estimation of individual indicators have varied slightly between the basins, due to varying degrees of data availability, differences in the specifics of the basin as well as in professional judgment. In some cases, attempts have been made to evaluate additional indicators, such as *aquatic plant species or phytoplankton richness* (e.g., Narmada). In some river basins, certain indicators could not be estimated (e.g., *degree of river fragmentation* in Krishna and Cauvery). These specifics are reflected in individual basin sections. However, every attempt was made to maintain the full spectrum of indicators for each river basin. In the light of many data uncertainties, the scoring system used here should be regarded as tentative and the entire approach, as still developing. In most of the cases, the indicators have been assessed at the basin-scale, which is obviously very coarse. But the same principles can be applied at smaller scales (subbasins or reaches), as illustrated with examples from Krishna and Cauvery rivers basins.

Krishna River Basin

The Krishna River originates in the Western Ghats at an altitude of 1,337 meters (m) above sea level, and flows to the Bay of Bengal through the peninsular states of Maharashtra, Karnataka and Andhra Pradesh. The total length of the river is approximately 1,400 km, and the total catchment area is 258,948 square kilometers (km^2). The interior of the basin is a plateau, which is at altitudes of 300–600 m above sea level. The river basin receives the major portion of its rainfall (up to 80% of the annual total) during the southwest monsoon period, which lasts from June to September.

Additional primary ecological data (Arunachalam 1999, 2004) exists for the Tungabhadra subbasin (one of the main tributaries of the Krishna River) and it has been evaluated separately. Each subbasin (Tungabhadra and the remaining part of the Krishna) has been additionally separated into three parts: 1) the headwater areas with a number of streams smaller than 10 km^2 (Arunachalam et al. 2005); 2) the middle reaches affected by reservoirs; and 3) the lower reaches (including delta), where development impacts are most pronounced (Figure 1). Each of the aforementioned areas has been studied in several subbasins, where field data collection had been carried out earlier (Arunachalam 1999, 2004). The presence of rare, endangered and unique aquatic biota has been rated on the basis of fish catch data summarized in the assessment of 327 species of freshwater fishes found in India (CAMP 1997) using the IUCN (1994) categories. The diversity of aquatic habitats has been studied in the field by Armantrout (1990) and Arunachalam (1999, 2000a, 2000b, 2004) using selected 100-m reaches of Krishna, Bhima, Tunga, Bhadra and other rivers in the basin. The proportional abundance of habitat types in the three areas (headwaters, middle and lower) has been estimated using the mean value of available habitats in several streams studied in each area (Jayaram 1995). The scoring system for habitat diversity is based on Arunachalam (2000a, 2000b), who has studied aquatic habitats for peninsular rivers in India and has identified their main types. The degree of regulation was not possible to estimate at the accepted separation of the basin due to uncertainties with the flow estimates at required river points. The estimation of other indicators is explained in tables 1–3.

Figure 1. A schematic map of the Krishna River Basin, showing the boundaries of the two main subbasins (Tungabhadra and the remainder of Krishna), separated into headwater, middle and lower areas for this study.

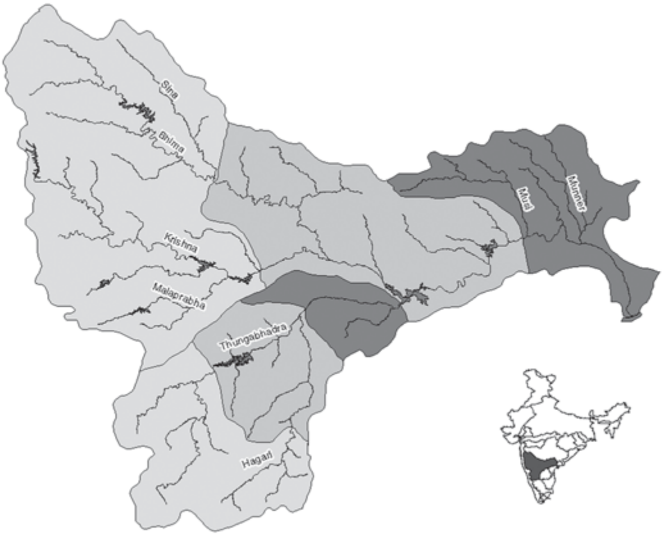


Table 2. Indicators for the Tungabhadra subbasin of the Krishna River Basin.

Indicator	Value	Score	Justification and Comments	Data Sources
Rare and endangered aquatic biota			An arbitrary but quantitative scoring system is used based on the percentage of endangered fish species of the total species in the basin (>20% endangered species—very high, 10–20%—high, 5–10%—moderate, 2–5%—low and <2%—minor or none).	Arunachalam (2004) CAMP (1997)
	High	4	Of the total 118 species in the subbasin, 12 are endangered and critically endangered in the headwaters (10.1%).	Arunachalam et al. (2002)
	Moderate	3	In the middle reaches, 5 endangered species are represented (4.2%).	
	Low	2	In the lower reaches only 3 such species are represented (2.5%).	
Unique aquatic biota			A similar scoring system is used as for endangered species—based on a percentage of unique fish of the total fish species in the basin (>20% endangered species—very high, 10–20%–high, 5–10%—moderate, 2–5%—low and <2%—minor or none).	Arunachalam (2004) CAMP (1997)
	Moderate	3	Out of 118 fish species, 9 endemics (7.6%) are present in the headwaters.	Arunachalam et al. (2005)
	Minor	1	In the middle and lower reaches, 2 endemic species (1.7%) are present. Headwater reaches support more unique fauna because the streams in the Western Ghats are mostly	

(Continued)

Table 2. Indicators for the Tungabhadra subbasin of the Krishna River Basin. (continued)

Indicator	Value	Score	Justification and Comments	Data Sources
			bedrock valleys and are strongly confined. Out of 11 endemic species 5 species (*Barilius canarensis, Glyptothorax trewavsae, Botia straita, Longischistura bhimachari* and *Hypselobarbus dobsoni)* have narrow distribution.	
Diversity of aquatic habitats	High	4	In the upstream reaches of Tunga and Bhadra, falls, cascades, pools, riffles, glides, runs and 'pocketwater' are all present.	Arunachalam (2004)
	Moderate	3	In the middle reaches, reservoir habitat types are wetlands and deepwater, while downstream of reservoirs and the reaches in between—runs, deep pools and backwater habitats are present.	Jayaram (1995) Scott (1989)
	Minor	2	In the lower reaches, the only habitat types are runs with fine sand and occasional large pools.	Arunachalam et al. (2005)
Presence of protected and pristine areas	1–3%	2	The subbasin has 1.62% as protected area with two wildlife sanctuaries (Bard and Ghataprabha) and the Kudremukh National Park. More forests can be protected as buffer zones of the Kudremukh National Park and sanctuaries.	Arunachalam (2004) Manjrekar (2000) Jayaram (1995)
Percentage of watershed remaining under natural vegetation	70–00%	5	In the headwaters almost all the streams are under natural cover type (90%).	Arunachalam (2004)
	50–70%	3	In the reservoirs and the reaches 10–15 km downstream of them, the percentage of natural cover is under 65%, but in most of the middle reach the percentage is under 50%.	Jayaram (1995)
	10–30%	2	In the lower reach in the Karnataka part up to the confluence of Tungabhadra with Krishna river: 28–30%.	(for middle and lower reaches)
Percentage of floodplain remaining under natural vegetation			Floodplains are present in the middle and lower reaches only.	
	30–50%	3	Middle reaches before the Tungabhadra Reservoir.	
	10–30%	2	From the Tungabhadra Reservoir towards the AP boundary.	
Percentage of aquatic biota that are exotics	0%	5	In the headwater reach there are no exotic fish species.	Arunachalam (2004)
	<5%	4	In the middle reaches, particularly—in the reservoir sector—introduced species of *Cirrhinus mrigala, Labeo rohita* are present. But the proportion in rivers upstream and downstream of the reservoir is still small in spite of having introduced these species 40 years ago.	Sugunan (1995)
Fish species relative richness	50–70%	4	Upstream reach is represented by 68 species (57.6%) of the total 118 recorded in the subbasin.	Arunachalam (2004)
	70–100%	5	Middle reach is represented by 78 species (66.1%).	
	30–50%	3	Lower reaches are represented by 31 species (26.3%).	Jayaram (1995)

(Continued)

Table 2. Indicators for the Tungabhadra subbasin of the Krishna River Basin. (continued)

Indicator	Value	Score	Justification and Comments	Data Sources
			A different scoring system should be designed, which which is based on the total number of species present in India, or in the region. But the estimates of the total number of species nationally vary from 327 (CAMP 1997) to 577 (Arunachalam 2004). If the latter figure is used as a benchmark, the basin is estimated to support 20.4% of this total species.	Ponniah and Gopalakrishnan (2000)
Human population density in the basin as a percentage of that in the main floodplains	<10%	1	Score is based on mean values from middle and lower reaches, which have an indicator value of 7%. Floodplains have been delineated using GIS.	District Planning Maps 2001, Karnataka. Census of India (2001)
Overall water quality in the basin	A	5	Headwaters are under relatively natural conditions with high levels of dissolved oxygen, low levels of TDS, very low alkalinity and no enrichment of nitrates and phosphates.	Arunachalam (2004)
	C	3	In the middle and lower reaches, non-point and point sources of pollution and nutrient enrichment from paddy fields contribute to the pollution.	Jayaram (1995) CPCB (1992)

Table 3. Indicators for the Krishna River Subbasin (excluding Tungabhadra subbasin).

Indicator	Value	Score	Justification and Comments	Data Sources
Rare and endangered aquatic biota			An arbitrary but quantitative scoring system is used based on the percentage of endangered fish species of the total species in the basin (>20% endangered species—very high, 10–20%—high, 5–10%—moderate, 2–5%—low and <2%—minor or none).	Arunachalam (1999) Arunachalam et al. (2002)
	Low	2	In the headwater reaches, based on surveys of 15 streams, 5 endangered species (3.6%) are identified (out of the total 140 species in the subbasin).	Arunachalam (2004)
	Moderate	3	In the middle reaches downstream of the reservoirs in Maharashtra and Karnataka 11 endangered species present (7.9%).	Jayaram (1995)
	Moderate	3	In the lower reach below the Tungabhadra River confluence with Krishna River 10 endangered species (7.1%) are present.	CAMP (1997)
Unique aquatic biota			A similar scoring system is used as for endangered species—based on the percentage of unique fish of the total fish species in the basin (>20% endangered species—very high, 10–20%—high, 5–10%—moderate, 2–5%—low and <2%—minor or none).	Arunachalam (1999) Arunachalam et al. (2002) Arunachalam (2004)
	High	4	In the headwaters, 11 unique species out of the	

(Continued)

Table 3. Indicators for the Krishna River Subbasin (excluding Tungabhadra subbasin). (Continued)

Indicator	Value	Score	Justification and Comments	Data Sources
			total 140 (7.9%) are present.	Jayaram (1995)
	Low	2	Middle and most of the lower reaches are represented by 4 species (2.8%).	CAMP (1997)
Diversity of aquatic habitats	Very high	5	In the headwaters a number of streams surveyed exhibit pools, riffles, glides, runs, alcoves/ 'pocketwater', etc.	Arunachalam (2004)
	High	4	Below the confluence with Tungabhadra, several streams were surveyed which have deep pools, falls cascades, riffles, rapids and glides.	Jayaram (1995)
	Low	2	In the lower reaches habitats are mostly riparian wetlands and wet hollows in delta.	
Presence of protected and pristine areas	<1%	1	In the headwaters, 0.97% of the area is protected with 5 wildlife sanctuaries (Koyna, Bhimsankar, Phansad, Radhnagiri and Chaprala).	Manjrekar (2000)
	3–5%	3	Nagarjunasagar Reserve is 4.7% of the area of the middle reaches.	Revenga et al. (1998)
	<1%	1	Mangrove ecosystem in the delta which needs to be protected has an area of 200 km^2. It could be considered for maintenance by means of environmental flow releases.	
Percentage of watershed remaining under natural vegetation	50–70%	4	Many headwater streams surveyed have the range of 55–68% of natural cover types.	Arunachalam (2004)
	30–50%	3	Middle reaches—below the Dhom Dam and Wai Town have the range of 38–47%.	Jayaram (1995)
	10–30%	2	Two streams surveyed in lower reaches had a range of 18–28% of natural cover types.	NSII (1991)
Percentage of floodplain remaining under natural vegetation			Floodplains are rare in the headwaters of Krishna and Bhima.	Arunachalam (2004)
	30–50%	3	In middle reaches in Maharashtra, most of the flood plains are flood hollows with natural cover types. In middle reaches in Karnataka below the impoundments, extensive cultivation of Bengal gram in the floodplain areas.	http://www.annauniv.edu
	10–30%	2	Below the confluence of Tungabhadra and Krishna and up to the Nagarjunasagar Reservoir. Overall, approximately 55% of the existing floodplains are under natural cover—mainly due to natural cover in protected areas and mangrove forests in the delta.	
Percentage of aquatic biota that are exotics	0%	5	In the headwaters there are no exotic fish species.	Sugunan (1995)
	<5%	4	In the middle reaches, including the reservoirs, the proportion of introduced species of *Catla catla*, *Cirrhinus mrigala, and Labeo rohita* is small. Native fish dominate the commercial fish catch.	Jayaram (1995)
	<10%	3	In the lower reach introduced species of Gangetic carps form 30% of the commercial catch. *Pangasius pangasius,* a native pangasid catfish, constitute	

(Continued)

Table 3. Indicators for the Krishna River Subbasin (excluding Tungabhadra subbasin). (Continued)

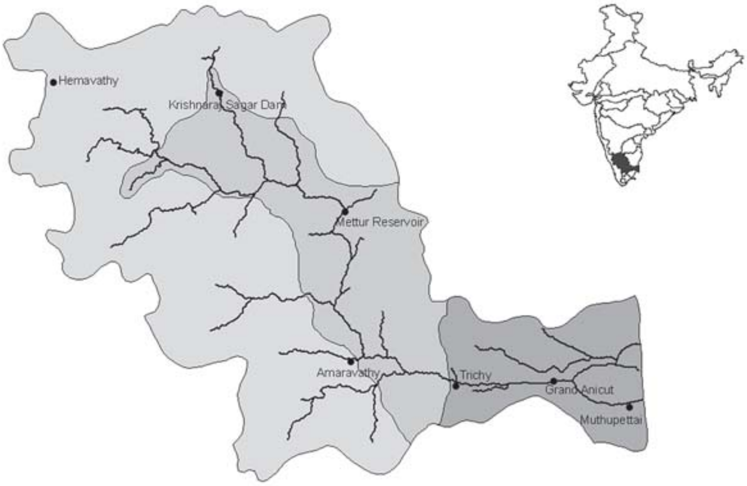
Indicator	Value	Score	Justification and Comments	Data Sources
			the major catch. In the delta, native marine and estuarine species are the major faunal component.	
Fish species relative richness	30–50%	3	The headwaters have some 41% of the total species in the basin.	Arunachalam et al. (2002)
	70–100%	5	The middle reaches support 71.4% of the total.	
	30–50%	3	The lower reach has around 41% of the total species in the basin. In the delta no primary freshwater species are present, but 40 estuarine and coastal marine species are recorded. A different scoring system should be designed, which is based on the total number of species present in India, or in the region. But the estimates of the total number of species nationally vary from 327 (CAMP 1997) to 577 (Arunachalam 2004). If the latter figure is used as a benchmark, the basin is estimated to support 24.2% of total species.	Arunachalam (1999) Arunachalam (2004) Ponniah and Gopalakrishnan (2000)
Human population density in the basin as a percentage of that in the main floodplains			In the headwaters floodplains are rare.	NSII (1991)
	20–40%	3	In the middle reach this proportion is 25.9%.	
	40–60%	4	In the lower reach this proportion is 43.6%.	
Overall water quality in the basin.	A	5	In all the headwater streams, the water quality is close to natural conditions.	Department of Environment (2004)
	C	3	Upstream of impoundments at Yadgiri Town (Bhima River), Haripur Ghat (Krishna) and below the reservoirs, Krishna River at Wai are polluted by sewage. In the middle reaches point sources from industries and sewage from towns exist.	Andhra Pradesh CPCB (1992)
	E	1	In the lower reaches textile, sugar and manganese mixing industries are sources of pollution.	Jayaram (1995)

Cauvery River Basin

The Cauvery River, with a total basin area of 87,900 km^2, originates from the Western Ghats in Karnataka State and extends over parts of Tamil Nadu and Kerala. The river flows through small patches of upstream jungle and gorges, followed by predominantly vast monotonous plains—into a diverse delta with Pichavaram mangroves. As in the case of the Krishna River, for this study, the Cauvery River Basin too, is broadly categorized into headwater, middle and lower (delta) areas. Several experimental subbasins have been studied (Figure 2) to determine the representative scores for each of the three areas.

The studies of the Cauvery River ecology mainly focused on fish (Hora 1942; Rajan 1963; Easa and Shaji 1995), and with more recent reports on the invertebrates (Jayaram 2000;

Figure 2. A schematic map of the Cauvery River Basin, showing the boundaries of headwater, middle and lower areas and sites where field data were collected.



Sivaramakrishnan et al. 1995). As in the Krishna Basin, CAMP (1997) data have been used, CR and EN and unique fish species (IUCN 1994) found in different experimental subbasins have been identified and their proportion of the total number of species has been calculated. A number of fish species in more than 50 sites in the headwater subbasins and 30 sites in the middle and lower reaches have been used to evaluate the overall fish richness (Arunachalam 1999, 2004; Jayaram 2000) as a proportion of the overall species reported in India. The averages of these proportions have then been calculated for headwater, middle and lower areas, to produce the representative indicator values. The diversity of aquatic habitats has been evaluated by estimating the number of different habitat types present in the same reaches from all three areas, based on the scoring system proposed by Arunachalam (2000a). The percentage of watershed and floodplain remaining in natural cover types has been calculated as the mean value of this percentage in experimental subbasins of headwaters and middle areas, based on field surveys by Arunachalam (2004). For the lower area, these indicators are assessed from the literature of Jayaram (2000). The percentage of exotic fish species is calculated (as in the case of rare and endangered species) using the primary data by Arunchalam (2004), and the published literature of Sugunan (1995) and Sreenivasan (1989). Six districts in Karnataka, three districts in Kerala, seven districts in Tamil Nadu and one district in Pondicherry have been used to approximate the human population density in the floodplains of the main river and its tributaries (NSII 1991). Other indicators are estimated as explained in Tables 1 and 4.

Narmada River Basin

The Narmada River, with a catchment area of 94,235 km^2 and total length of 1,312 km, is the largest west flowing river on the Indian Peninsula (figure 3), crossing three states—Madhya Pradesh (MP), Maharashtra (MS) and Gujarat (GS). The climate ranges from temperate at the source to subtropical at the outlet. The rainfall varies from between 1,400–1,700 millimeters (mm)

Figure 3. A schematic map of the Narmada River Basin.

in the upstream parts to approximately 130 mm in the estuary. Narmada flows through the only rift valley of India, which is the alluvial tract between Jabalpur and Handia. It is over 320 km long and approximately 80 km wide, and is the most intensely cultivated part of the basin. In the estuarine part, the main river course divides into two branches before joining the sea. Although, the altitudes are generally under 1,000 m above mean sea level (amsl), Narmada is essentially a mountainous river tucked between the two ranges. The banks of Narmada are stable and the river lacks floodplains, which are extensive in other major Indian basins. Pools and waterfalls are the other characteristic features of Narmada.

Through most of its course, Narmada has prime quality forests that facilitate the maintenance of its flow throughout the year. These forests are unique for India and are rich in biodiversity, hosting panthers, sloth bears, sambars, barking and spotted deer, black bucks, wild boar, porcupines, foxes, hyenas, tigers, wildcats (including the endangered caracals), flying squirrels, jackals, blue bulls, the four-horned chinkara (the Indian gazelle) and many others. The prime forest area at Khandwa—the Chandragharh Forest—supports the endemic tree species of Anjan (*Hardwickia binata*), which attain considerable heights.

Narmada basin hosts some 20 million people, of which the majority is tribal people who depend entirely on the river and its forests for their livelihood. The population stress on the river is, however, low compared to other basins in India. Narmada has only three townships, and in two of these the population is less than 70,000 as per 1991 census. Only the major city of Jabalpur has a population of over 0.7 million.

This mean annual river flow of over 45.6 billion cubic meters (BCM) remains largely untapped at present, although heavily committed for development. Over the next few decades, the construction of 29 large, 450 medium and some 3,000 minor dams is planned (Alvares and Billorey 1988). At present, the major regulation structures in the basin are limited to the Barna and Tawa dams (on tributaries), constructed in the 1970s and the Bargi Dam on the main stream, completed in 1991. The estimation of indicators for Naramada basin in explained in Tables 1 and 5.

Periyar River Basin

The Periyar River (Figure 4) with a total catchment area of 5,243 km^2 and a length of under 300 km, originates at an altitude of 1,830 m amsl in the Western Ghats. The annual rainfall ranges

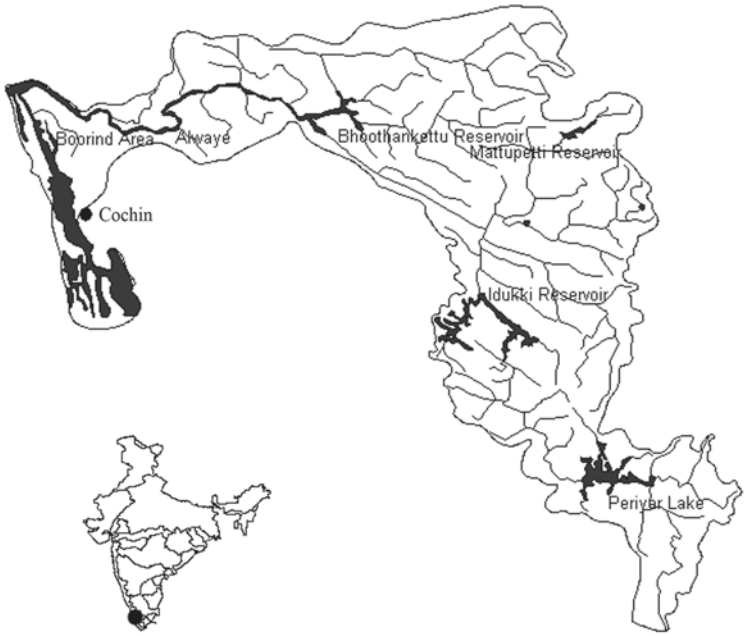


Figure 4. A schematic map of the Periyar River Basin. The black areas near Cochin are backwaters.

from 4,000 mm in the upstream parts to 200 mm in the coastal areas. The basin is located primarily in the Kerala State. Kerala has 41 west flowing rivers carrying a total annual discharge of 72.7 BCM—higher than the total flow of large rivers like Cauvery or Krishna (Sugunan 1995). The Periyar mean annual flow volume of 12.3 BCM is the largest among the river basins in the Western Ghats.

The characteristic feature of the basin is the Western Ghats' forests, where about 70 percent of the trees are endemic to the region (due to its geographic barriers), and where streams are home to a number of endemic fishes (Pascal 1996). The Periyar Lake in the upstream part of the basin is surrounded by such forests, renowned for sanctuaries like the Tiger Reserve—one of the 18 biodiversity hotspots of India (Pascal 1996), a home for several endangered species. More downstream, the river meanders through Malayattoor, Kalady and Alwaye—which are holy places of worship, attracting up to 50 million pilgrims annually. In its most downstream parts, the river flows through the 'Eloor industrial belt' into the Cochin estuary. The basin has 9 irrigation schemes and 16 hydroelectric projects. The total volume of all reservoirs in the basin is estimated to be 3.28 BCM (KSEB 2005). Of these, the Idukki Reservoir is the largest (around 2 BCM). Compared to other rivers in the Western Ghats, Periyar is relatively better studied ecologically. The estimation of indicators for Periyar is explained in Tables 1 and 6.

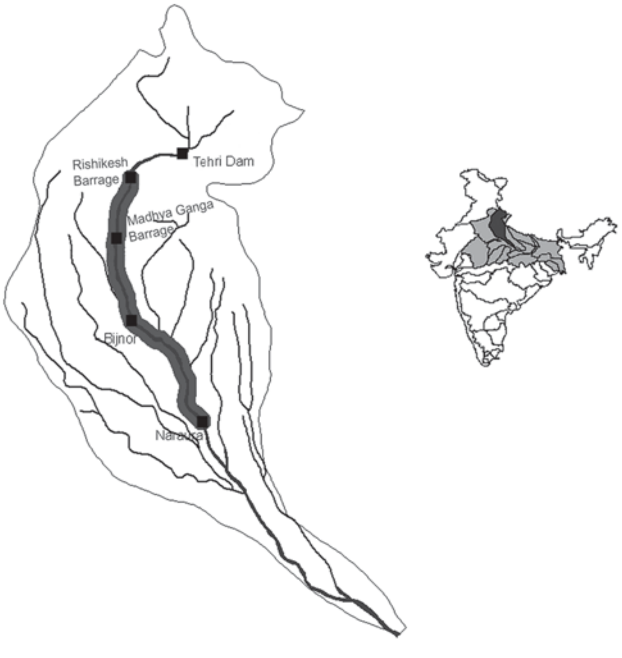
Ganga River Basin (Rishikesh to Naraura Reach)

Ganga is the longest (2,525 km) river and the largest river basin in India. It supports over 300 million people across its 800,000 km^2 catchment area in India, and also extends into Bangladesh, China and Nepal. The mean long-term annual river flow is estimated to be

525.0 BCM. The live storage capacity in the basin has increased significantly over the past 50 years—from 4.2 to 37.8 BCM (http://wrmin.nic.in). In addition, a substantial storage capacity of over 17.0 BCM will be created on completion of the current projects, while an additional storage of over 29.6 BCM is planned (http://wrmin.nic.in) for the future. Therefore, after the construction of all currently proposed dams, about 30 % of the annual utilizable flow (i.e., 250 BCM) could be stored.

The above developments will threaten the aquatic ecology of the basin. However, very few ecological studies have been conducted in the basin to date. While the entire basin should ideally be considered for ecology studies, it is not possible to do so in a limited study like this one. As an *imperfect* substitute for the basin-wide study, an attempt has been made here to describe the ecological value and condition of a 295 km stretch of the Ganga, between Rishikesh and Naraura, where WWF-India has been coordinating the Dolphin Conservation Program (Figure 5). The area covered under the study is about 16,780 km^2 in the Uttar Pradesh and Uttaranchal States.Some ecological information can be derived or inferred from sources like Behera (1995),Payne et al. (2003), and Rao (1995). These have been supplemented by other, more 'global' sources, like the World Resources Institute's Earth Trends database and its publications as well as Dudgeon (2000), Menon (1999, 2004), Kottelat and Whitten (1996), and Nilsson et al. (2005). In addition, the Census of India (2001) and maps from National Atlas and Thematic Mapping Organisation (NATMO) have been used. In the study reach itself (the 295 km stretch of the Ganga, between Rishikesh and Naraura), there are no major water storage dams, except for the Tehri Reservoir, which is located upstream.

Figure 5. A schematic map of the Ganga River Basin, showing the location and extent of the subbasin upstream of Naraura as well as the enlarged map of the Ganga reach between Rishikesh and Naraura reaches.



Indicators and Trends in Study Basins

Krishna River Basin

Tables 2 and 3 summarize the results for Tungabhadra subbasin and the rest of Krishna River Basin, respectively. Both subbasins are more natural in the upstream areas, with diverse and relatively unfragmented habitat, limited or no exotics and a high percentage of natural cover types. Both subbasins are broadly similar in most of the indicator scores, which have a clear tendency to deteriorate downstream with the progressive increase of human pressure. The exception is the higher richness of fish in both subbasins in their middle reaches, which is partially due to the effects of tributaries that create more diverse and deeper habitats. In the lower reaches, however, species richness drops due to overfishing that occurs downstream of reservoirs and the impacts of urbanization. The practice of using trawl nets with a small mesh size (8–10 mm), for example, almost eliminates the entire fish population (Arunachalam, personal observations). In the Krishna subbasin, the middle reaches support more species than the headwater and lower reaches, primarily due to the increasing size of the streams that still remain in a more natural condition compared to the lower areas. The lower reach, including the delta (Jayaram 1995), has limited freshwater species, but is represented by 40 species of brackish and coastal marine fish.

Overall, the pressure in the upstream parts of the basin has been relatively limited compared to the lower reaches, where the deteriorating trends are alarming. River discharge, for example, has been decreasing at the outlet from 1968 onwards. In addition, water-sharing conflicts exist between the states of Karnataka and Andhra Pradesh. The major flow of water is obstructed by the increasing number of large- and medium-sized dams, which has completely changed the sediment regime of the river and fragmented its habitats in the middle and lower reaches. Krishna delta, with a mangrove forest area of some 200 km^2, faces threats of deforestation, overgrazing, harvesting of juvenile fauna and expansion of agriculture and shrimp aquaculture.

Cauvery River Basin

Field studies in the streams of the Cauvery River Basin, from the headwater reaches to their outlets, revealed significant habitat heterogeneity, which is exploited by guilds of fish species (Table 4). Headwaters tend to support more endangered fishes and, as such, these streams can be used as ‘reference sites’ for the entire basin. These headwater streams have high gradients and predominantly bedrock substrates, and endangered fishes are confined to such rocky stream types. Similar sites are found in the middle areas, but to a lesser extent. In the lower reaches, however, fish diversity and their formerly abundant population are declining.

Most protected areas are found in the headwaters, less than one percent is found in the middle and lower reaches, while the mangrove swamps of Pichavaram and Muthupet lagoons—are protected by the State Forest Department. Some pristine areas may still be declared protected in the upstream areas (e.g., in the catchments of Moyar, Bhavani and Amaravathi streams). In the middle and lower reaches there are a few heritage sites such as the Vishnu Temples at Srirangapatnam, Sivasamudram and Srirangam; and Kaveri-Poompattinam (an ancient capital of the Cholas Kingdom in the first century AD). Most of the headwaters are still under natural vegetation cover, but the pressure from human settlements is increasing progressively downstream.

Table 4. Indicators for the Cauvery River Basin.

Indicator	Value	Score	Justification and Comments	Data Sources
Rare and endangered aquatic biota			A similar scoring system as in tables 2 and 3 above has been used.	CAMP (1997)
	High	4	Streams in headwaters have 16 endangered fish species (12%) out of a total of 135 species in the basin.	Arunachalam (1999, 2004)
	Moderate	3	The reservoirs Hemavathy, Kabini, Krishnarajasagar, Markonahalli and Harangi, and streams below them in the middle reaches, support 8 endangered species (6%).	
	Low	2	In the lower reaches, only 3 endangered species are found (2%). Common tolerant species such as *Pseudophromanus cupanus, Puntius filamentosus,* etc., occur in lower reaches. Near delta, no rare and endangered freshwater fish species are present.	
Unique aquatic biota			A similar scoring system as in tables 2 and 3 above has been used.	CAMP (1997)
	High	4	Headwater reaches host all 22 species that are endemic native fish (16% of total basin species).	Arunachalam (1999, 2004)
	Low	2	Middle reaches have 6 endemic species (4.5%).	
	None	1	Lower and coastal areas have no unique fauna.	
Diversity of aquatic habitats	Very high	5	In headwaters, habitats are diverse with falls, cascades, pools, riffles, glides, runs and 'pocketwater'. Bedrock and boulders and the leaf litter with woody debris contribute to fish habitat heterogeneity in headwaters (Western Ghats).	Arunachalam (1999, 2000b, 2004)
	Moderate	3	In the reservoirs, the habitat types are wetlands (limnetic zones) and deepwater (euphotic zone). In the middle reaches of the river, run, deep pools and backwaters are prevalent.	Arunachalam et al. (2005)
	Moderate	3	In lower reaches, most habitats are riparian wetlands and floodplains with runs, mangrove swamps and lagoons contribute to habitat heterogeneity.	
Presence of protected and pristine areas	5–10%	4	Compared to the overall watershed area, the headwaters have some 7.8% of the area protected with seven wildlife sanctuaries (Biligiri Rangaswamy, Brahmagiri, Cauvery, Nugu, Thalacauvery, Mudumalai and Wynaad) and four National Parks (Bandipur, Rajiv Gandhi (Nagarhole), Mukurthi and Silent Valley).	Manjrekar (2000) Dave (1957)
	<1%	1	Kaveri-Poompattinam—the ancient capital of the Chola Kingdom in the estuary. Pichavaram mangroves and the lagoon in the Vedaranyam Wildlife Sanctuary are the major protected spots or heritage sites. Vedaranyam Swamps and the Muthupet Lagoon can be declared as RAMSAR sites.	

(Continued)

Table 4. Indicators for the Cauvery River Basin.(Continued)

Indicator	Value	Score	Justification and Comments	Data Sources
Percentage of watershed remaining under natural vegetation	70–100%	5	In the headwater reaches almost all streams surveyed are under natural cover in the range of 74–85%. Only tea and coffee plantations reduce this proportion.	Arunachalam (2004)
	30–50%	3	In some streams surveyed in the middle reaches, this percentage is up to 53%, but the lowest part of themiddle reaches—20 km from the reservoir towards coastal area—is under 50%.	Jayaram (2000)
	<10%	1	Estuarine area has a low natural cover proportion, only mangrove forest Pichavaram and distributaries raise it up.	
Percentage of floodplain remaining under natural			Floodplains are present only in middle and lower reaches.	Arunachalam (2004)
	30–50%	3	From Mayanoor to upper anicut, the floodplains are less than 50% under natural vegetation. This stretch forms about 30–40% of the overall floodplains in the basin.	Jayaram (2000)
	<10%	1	Below the Grand Anicut floodplains are impacted by rice and banana cultivation. In the delta region floodplains are mostly converted into shrimp farms.	
Degree of flow regulation	10–20%	4	Taken from the cited source as is (19%). More detailed estimation was not possible due to uncertainties or absence of flow estimates at required points in the basin.	Nilsson et al. (2005)
Percentage of aquatic biota that are exotics	>0%	5	In the headwaters there are no exotic fish species.	Arunachalam (2004)
	<5%	4	In the middle and lower reaches, all channels below impoundments and the entire river from Bhavani Town, the proportion of exotic fishes are low (<5%). (Almost all reservoirs are dominated by introduced exotics and gangetic carps. Of 58 species recorded in reservoirs, the introduced species form some 41%. In the biomass of commercial catch the introduced species constitute 80–90% and the native species —less than 5%).	Sreenivasan (1989)
Fish species relative richness	50–70%	4	Headwaters host 68 species (50% of the total in a basin).	Arunachalam (1999, 2004)
	50–70%	4	The middle reaches host 72 species (53% of the total).	
	10–30%	2	Approximately 18% in the lower reaches (but in the delta—less than 5%). A different scoring system should be designed, which is based on the total number of species present in India, or in the region. But the estimates of the total number of species nationally vary from 327 (CAMP 1997) to 577 (Arunachalam 2004). If the latter figure is used as a benchmark, the basin is estimated to support 23.62% of total species.	Jayaram (2000) CAMP (1997). Ponniah and Gopalakrishnan (2000)

(Continued)

Table 4. Indicators for the Cauvery River Basin.(Continued)

Indicator	Value	Score	Justification and Comments	Data Sources
Human population density in the basin as a percentage of that in the main floodplains	40–60%	4	Estimated for middle and lower reaches only. In the lower reaches, the ratio is 42.4% and in middle—51%.	NSII (1991)
Overall water quality in the basin	A	5	Most of the headwater streams surveyed have high levels of dissolved oxygen, low levels of total dissolved solids, very low alkalinity and hardness and no enrichment of nitrates and phosphates.	Arunachalam (2004) Jayaram (2000)
	C	3	In the middle reaches, non-point and point sources of pollution increase.	CPCB (1992)
	D	2	High pollution from industries in the stretch of delta except the Pichavaram mangroves and the Muthupet lagoon regions.	

Perhaps the major basin-specific feature that is adversely affecting basin ecology is the expansion of coffee, tea and, to a limited extent, cardamom plantations. The high elevation in the upstream parts of Cauvery creates ideal conditions for these cultures. These developments, due to the removal of riparian forests, may lead to denudation. In addition, the associated population growth may lead to the abstraction of water from first and second order streams for domestic use, while the increased waste loads may eliminate the endemic fauna. Habitats in the headwaters are still up to 70 % in an undisturbed condition. This is analogous to habitat intactness and can be regarded as wilderness (Mittemeier et al. 2003), hence needs protection.

Cauvery River at present is highly fragmented by various impoundments (Kathiresan 2000). While mangrove vegetation tends to be more luxuriant at lower salinities (Kathiresan et al. 1996), some areas in the delta are being degraded mainly due to high salinity levels, resulting from the reduced freshwater inflow (MSSRF 1998). A further reduction or a continuation of the current limited inflow will be detrimental to the coastal areas (Ittekkot et al. 2000).

Fishes upstream are affected directly by physical barriers (e.g., Lower Anicut, the Great Anicut and the Upper Anicut) to their migration, by the inundation or drying out of spawning grounds (upstream or downstream of dams), which is reflected by the poor species richness in the lower reaches. Some indigenous ichthyofauna (e.g., the anadromous fish, *Tenualosa ilisha,* or *Puntius* spp., which used to form 28% of the landings in 1943–1944) have completely disappeared from Cauvery after the construction of the Mettur Dam (Sugunan 1995). Population density in Cauvery is among the highest in the world (350 people/km^2 compared to the world's average of 42 people/km^2). The population growth is also 2.5 times the rate of the world's population growth as a whole, which is seen as a major threat to the vast native forests in the basin and a significant contributor to their disappearance in the not too distant future (Cincotta and Engelman 2000).

Narmada River Basin

Earlier studies of CIFRI (1993), NPA (1987), RRSL (1987), and Dubey (1993) did not identify any endangered, rare or unique species of fish in the basin. The only *rare* organism reported was the water monitor lizard, which lived in the estuary (Alvares and Billorey 1988). There is limited evidence, however, that up to 10 species in the basin may be classified as endangered and 8 of these as unique (Arunuchalam, unpublished data). Narmada and its main tributaries are rich in habitat types, which include pools, gorges, waterfalls, deep waters, etc. The river has a number of pristine and protected areas: it flows through Bandhavagarh National Park (430 km^2), Kanha Biosphere Reserve (940 km^2), Satpura National Park (524 km^2) and three forest reserves of Mandla, Seoni and Hoshangabad with areas of 110, 416 and 449 km^2, respectively. A number of protected areas and forest reserves on the one hand and the relatively low population density on the other hand, mean that the basin remains largely under natural cover. At present, Narmada has only a few structures and flow fragmentation is relatively low. However, the planned storage construction will increase flow fragmentation significantly. According to Rao et al. (1999), fishes of Narmada predominantly belong to the local endemic carp group (Mahseer, Hilsa and Catla) and Dubey (1993) reported that exotic fishes like grass or silver carp do not breed in the basin.

An attempt was made here to distinguish between fish, aquatic plants, phytoplankton and zooplankton species richness (Table 5). The richness of *aquatic plants* is related to the degree of nutrients. Narmada has a relatively moderate aquatic flora (Unni 1996), reflected in a moderate

Table 5. Indicators for the Narmada River Basin.

Indicator	Value	Score	Justification and Comments	Data Source
Rare and endangered aquatic biota	None	1	The CIFRI (1993) studies suggested that there are no endangered or threatened fishes. Some unpublished sources suggest that up to 10 species may beconsidered endangered.	Karamchandani et al. (1967) Dubey (1984) Rao et al. (1991)
Unique aquatic biota	None	1	There are no reports on unique aquatic fish biota in the Narmada Basin, though studies have been conducted over a 50-year period on distribution of fish species.	Chatterji et al. (1993) Nath and Shrivastava (1999) Dubey (1993)
Diversity of aquatic habitats	High	4	Narmada has diverse habitats, including pools, gorges, waterfalls and deep waters similar to other major river systems in India.	Rao et al. (1991, 1999) Unni (1996)
Presence of protected or pristine areas	>10%	5	The Narmada Basin includes many sanctuaries, and 38% of all forests are forest reserves.	Alvares and Billorey (1988)
Sensitivity of aquatic ecosystem to flow reduction	Moderate	3	The construction of the Tawa Dam resulted in a reduction of water depths and loss of carp breeding grounds, spawning and feeding in the central 240 km stretch of the Narmada Basin.	Nath and Shrivastava (1999)

(Continued)

Table 5. Indicators for the Narmada River Basin. (Continued)

Indicator	Value	Score	Justification and Comments	Data Source
			Carp dominates Narmada fish and flow reduction is the reason for reduced carp fisheries.	
Percentage of watershed remaining under natural vegetation	10–30%	2	The National Remote Sensing Agency reported that 21% of the Narmada Basin has natural forest cover types.Others quote 38%. The likely average is around 30%.	Forest Department, Government of Madhya Pradesh Reconnaissance Survey. Alvares and Billory (1988)
The degree of flow regulation	0–10%	5	Calculated as the ratio of total storage to long-term mean annual flow at the outlet. The actual live storage capacity in 2006 is 2.07 BCM. Annual mean outflow is 45.6 BCM, and the ratio is around 4.5%.	CWC (2006)
Percentage of watershed closed to movement of aquatic biota by structures	10–30%	4	At present, this indicator is low and the score is thus high, but if the reservoir construction goes as planned, the entire river basin will be fragmented and the percentage of structures watershed closed could grow up to 100%.	Alvares and Billorey (1988)
Percentage of aquatic biota that are exotic	None	5	No exotic fish species have been reported.	Rao et al. (1991) Dubey (1993)
Species' relative richness, including fish, aquatic plants, phytoplankton and zooplankton	Moderate	3	Narmada has 76–84 fish species according to existing estimates, which is relatively low compared to the total number of species in India (<14%). It supports 19 species of aquatic vegetation, relatively low compared to other rivers. The total number of Phytoplankton species is 174 in the upstream and declines towards the middle stretches. Greater water current reduced the phytoplankton numbers to 34 species downstream. Zooplankton: maximum number of 72 rotifer species is reported only from Narmada and nowhere else in India. Four new species of zooplankton have recently been identified. The likely overall score of aquatic species richness in the basin is moderate.	Nath and Shrivastava (1999) Dubey (1984) Unni (1996) Sharma and Naik (1995) Dubey (1993)
Overall water quality in the basin	Class B	4	Class A is from the source to Mandla (200 km), class C from Mandla to Jabalpur stretch (100 km), class B—the stretch up to the confluence with Kunti River (540 km), class C from confluence with Kunti River up to Bharuch, and class D—downstream of Bharuch (8 km). Overall water quality is class B (40% under class C, 40% under class B and about 20% under class A),	

score and range of 10–30 %. This score, however, is based on observations at three sites in headwaters, while the data on other parts of the river are absent. The quantitative studies on *phytoplankton* (e.g., in Ganga) show high fluctuations and vary between thousands and millions of cells per liter, when correlated with the degree of pollution. The clear waters of Narmada have relatively lower numbers of phytoplankton. The distribution and composition of *zooplankton* indicate the status of water quality. The information on zooplankton is available for many Indian rivers. The characteristics of zooplankton for the Narmada reflect a good condition at present. The diversity of naturally occurring periphytic algae and diatoms as well as the diversity of naturally occurring zooplankton are, however, quite high in Narmada waters. Despite the limited data on actual constituents, the overall water quality is good (Unni 1996) and mostly free from pollution throughout its course, except for a small estuarine part of over 20 km.

Neither significant changes nor rapid developments are likely in the Narmada River Basin, since even basic infrastructure, like roads, is lacking. The hilly terrain of the basin is a major disadvantage for development. Agriculture is the main source of livelihood for the local ethnic groups. Fast urbanization is unlikely, and the negative impacts of existing towns on the river (e.g., on water quality) will be limited even in the next 25 years. At the same time, a large number of mainstream dams, if constructed without provisions of fish ladders and environmental flow releases, will definitely have adverse impacts on the river ecology. Lack of flow, decline in dominant fisheries, lentic conditions in dams and resultant eutrophication and waterborne diseases are some of the potential negative impacts in the long-term.

Periyar River Basin

For a relatively small basin, Periyar has a number of endemics and several threatened species (Kurup et al. 2001) as well as a range of various habitat types (Table 6). Thirty percent of the basin area is covered with dense pristine forests, parts of which are crossed by the river, and include wildlife sanctuaries. Like other west flowing rivers, the Periyar has no floodplains. The introduction of exotic fishes into reservoirs has lead to a decline in the abundance of endemic fishes. However, in the Periyar River itself, the exotics have not been reported so far. Various sources have reported variable numbers of fish species in different parts of the basin, varying from 27 in the Periyar tributaries, to 150 in the downstream parts (Arun 1998; Arunachalam 2000b). The basin is rich in fish species, hosting approximately 70 % of the species found in the Western Ghats and a significant proportion of the species found in India. In addition, CAMP (1997) identified a variety of endemic species found in the Periyar. As such, a proposition was made to declare the upper reaches of the Periyar, a fish sanctuary (Joseph 2004). However, no aquatic plants have been recorded in the basin.

A major negative trend in all the rivers in the Western Ghats is the construction of dams. The existing hydroelectric projects (e.g., Idukki) and the four proposed projects in the Periyar (additional fragmentation in the already significantly fragmented main river) pose threats of flooding to some of the primary forests. Another major impact is, sand mining, which has been fuelled by the construction boom in Kerala. Sand mining has affected the stability of river banks leading to loss of land and rendering large areas flood-prone. The quantity of sand that could be extracted safely is 19,178 tonnes annually, but the actual quantity removed is 30 times more (Pratapan 1999). Indiscriminate sand mining deepens the river channel, which in turn promotes saline intrusion in the coastal area.

Table 6. Indicators for the Periyar Basin.

Indicator	Value	Score	Justification and Comments	Data Sources
Rare and endangered aquatic biota	Very high	5	Periyar basin has 5 critically endangered fishes and 14 threatened species. Fourteen species have become extinct. Some fish species disappeared over the past few years, including some cyprinids, goby, catfishes and eels.	Arun (1998) Kurup et al. (2001)
Unique aquatic biota	Very high	5	Fifty-six percent of the endemic fishes of Kerala are reported from Periyar (32 species), which makes it a unique ichthyfaunal basin of southern India.	Kurup et al. (2001) Arun (1998)
Diversity of aquatic habitats	Very high	5	Many threatened fish species inhabit pools, streams, runs, cascades—a diverse aquatic habitat types' system.	Arunachalam (2000a)
Presence of protected and pristine areas	Very high	5	The river flows through the famous Periyar Wildlife Sanctuary. Latest satellite imagery shows that around 30% of the basin is covered by dense pristine forests.	
Sensitivity of aquatic ecosystem to flow reduction	High	4	Multiple dams reduced flow which leads to decline in fish diversity, extinction of fish, prawns and shrimps —particularly in lower reaches. Large-scale fish mortality between Edamalayar and Eloor industrial sites are reported as well as algal bloom of *Oscillatoria sp*. Given the number of impacts and that Periyar is a relatively small river, the sensitivity to further flow reduction is high.	Joseph (2004)
Percentage of the watershed under natural vegetation	30–50%	3	National Remote Sensing data shows 30% of the watershed is covered by dense natural forests.	Joseph (2004)
Degree of flow regulation	20–50%	3	Calculated as the ratio of total storage capacity (3.27 BCM) to long-term mean annual flow volume at the outlet (12.3 BCM), which equals 25%.	KSEB (2005)
Percentage of the basin closed to movement of aquatic biota by structures	70–100%	1	The construction of 15 dams and wiers have almost closed the river system to movement of the biota through the basin.	
Percentage of aquatic biota that are exotic	<10%	3	Some species have been introduced in reservoirs (carp), which can be found in streams as well, at present.	Sugunan (1995)
Fish species relative richness	Very high	5	The basin is very rich in fish species having 208 species out of the total of 287 species in the Western Ghats (70%) or out of estimated total 577 in India (36%).	Joseph (2004)
Overall water quality in the basin	Class B	4	Water quality of the upstream and middle reaches is, as a rule, in class B. The water quality was rated as class C in the most downstream parts.	Singh and Anandh (1996) Joy and Balakrishnan (1990)

Another major threat in the basin is, water pollution. The physico-chemical analyses and reviews of the Periyar River water quality are available from 1976 onwards for a period of 25 years (Paul and Pillai 1976, 1981). These analyses show a consistent decline in: pH and oxygen levels; and an increase in: water temperature, radioactivity, pesticide pollution, and levels of heavy metals. Crabs and prawns that were found downstream have now become almost extinct due to water pollution (Joseph 2004). Greenpeace (2003) describes the 'Eloor industrial area', which is located in the downstream of the Periyar River, as one of the most vulnerable 'hotspots' of industrial pollution in the world. A parallel reduction in the flow of water will further increase algal blooms, resulting in occasional 'fish kills' as has already been experienced in the past.

Ganga River Basin (Rishikesh to Naraura reach)

The indicator values for this reach of the Ganga River are summarized in table 7. Ganga is the top basin in India with regard to fish species richness, but estimates of the total number of species vary significantly. The World Bank identified about 350 species (Kottelat and Whitten 1996), while Talwar (1991) reported 375 species. Of these, the estimates of freshwater species are between 104 and 161 (Menon 1999; Payne et al. 2003). In the study reach between Rishikesh and Naraura, Behera (1995) recorded 82 species of fish. Of these 4 to 10 are threatened or endangered according to different sources (Menon 1999; Behera 1995; Arunachalam, personal observations). These include the 'endangered' *Tor tor*, a Mahseer, *Bagarius bagarius*, *Pangasius pangasius*, and *Rita rita* (Behera 1995). In addition, 12 species of freshwater turtles are present, out of which 6 species are considered endangered in terms of Schedule I of the Indian Wildlife Protection Act, 1972 (Rao 1995). In the same stretch, two species of crocodile *Crocodylus palustris* and the *Gavialis gangeticus,* locally known as 'Gharial', are found. Both are considered *endangered* (IUCN 1994). The Common Indian Otter (*Lutra lutra*), and Smooth Indian Otter (*Lutra perspicillata*), have also been sighted in this stretch of the river. Both species are classified as threatened (IUCN 1994). More than 100 species of birds, both migratory and residential have been sighted (Behera 1995), of which several are endangered. The area around Naraura was proposed as a potential bird sanctuary in 1978 (Rao 1995); 51 species of aquatic insects and 15 species of mollusks have also been observed in this area.

By comparing the list of fish species from the stretch (Behera 1995) with the list of endemic fish species of India (Karmakar and Das 2004), it is inferred that *no endemic freshwater species of fish* have been reported from the stretch. However, one species of Crocodile, *Crocodylus palustris*, twelve species of turtles and one aquatic mammal species, *Platanista gangetica*—the Gangetic Dolphin, have been recorded (Rao 1995). Though the Gangetic Dolphin is also found in the Brahmaputra, it is considered *unique* to the entire Ganga-Brahmaputra-Meghna (GBM) basin, and its characteristics that separate it from the Irrawady and Indus Dolphins have been well documented (Behera 1995). Though the crocodile is not unique to the Ganga system, it is an 'endangered' animal as per IUCN classification (IUCN 1994), as such, it is protected under Schedule I of the Wildlife Act, 1972. Although these species are not unique in the strictest sense, their presence warrants the conservation of this reach.

The Ganga becomes a mature river after Haridwar, flowing over hundreds of meters of alluvium. In the upper part of the reach, the *aquatic habitats* include riffle areas, rocky, sandy and muddy river banks, while the lower part is dominated by sandy and muddy banks and deep pools (Rao 1995). The shallow parts of the river turn into islands during low flows and thereby become good nesting grounds for turtles and island breeding birds.

Table 7. Indicators for the Rishikesh–Naraura reach of the Ganga River Basin.

Indicator	Value	Score	Justification and Comments	Data Sources
Rare and endangered biota	High	4	There are at least 4 (and according to other estimates—up to 10) endangered freshwater fish in the reach. In addition, in the study reach there are: endangered Gangetic Dolphin, 6 endangered turtle species, 2 species of endangered crocodile, 2 species of threatened otter, and several endangered bird species.	Menon (1999) Dudgeon (2000) Rao (1995) Behera (1995)
Unique Aquatic Biota	High	4	Gangetic Dolphin is unique and 60 fish species of the study stretch are endemic.	Behera (1995) Menon (1999)
Diversity of aquatic habitats	Moderate	3	Presence of upstream reservoirs, muddy, sandy banks and fast flowing reaches as well as formation of islands during low flows offer relatively diverse habitats for wildlife.	Rao (1995)
Presence of protected and pristine areas	>10% of the reach	5	The Brijghat–Naraura stretch is a Ramsar site and the Hastinapur Wildlife Sanctuary is located close to Madhya Ganga barrage.	
Sensitivity of aquatic ecosystems to flow reduction	Moderate	3	With diversions from the Ganga ongoing for over 100 years, the ecosystem would have 're-adjusted' to the reduced flows. Rapid increases of summer flows (associated with glaciers melting in Himalaya) have been recorded leading to submergence of small islands used by turtles. Overall, given the river size, the sensitivity is still moderate.	
Percentage of watershed under natural vegetation	10–30%	2	The historical destruction of forests is estimated to be over 80%. The trend seems to be reversing due to focus on plantation in Uttar Pradesh. It may, however, be misleading since the plantations may create monocultures.	Revenga et al. (1998)
Percentage of floodplains remaining	<10%	1	The current width of the floodplain is in the order of 2–3 km compared to anecdotal evidence of several tens of km width of flooding in the past.	R. Sinha (pers. comm.)
Degree of flow regulation	10–20%	4	While there has been little storage in the basin before, the recent construction and commissioning of Tehri Dam has started filling up a large 3.54 BCM reservoir. Four barrages in the study stretch also contribute to flow regulation, which remains relatively low—with a correspondingly high score.	Behera (1995)
Number of dams or other significant barriers per km of river channel	~0.01333	3	This is an indicator of fragmentation. Some newer structures have fish ladders that could 'reduce' fragmentation but their effectiveness is unknown. Four barrages exist over a stretch of approximately 300 km. However, since the river is not heavily regulated, and during monsoon upstream movement by aquatic biota is possible, a lower score is given.	

(Continued)

Table 7. Indicators for the Rishikesh–Naraura reach of the Ganga River Basin. (Continued)

Indicator	Value	Score	Justification and Comments	Data Sources
Percentage of aquatic biota that are exotic	>20%	1	Of about 80 fish species recorded in the study area, 60 are considered native and the rest as alien.	Behera (1995) Menon (1999)
Aquatic species richness	Very high	5	Ganga has the highest fish species richness compared to any other river in India—350–375 species (according to various estimates) out of estimated 577 total species (66%). This is partially determined by its mere size crossing many physiographic zones. The study stretch has around 82 fish species, which is about 22% of the basin's total number of fish species, but is much lower in the national context (14%).	Kottelat and Whitten (1996) Talwar (1991) Behera (1995)
Human population density as a percentage of that in the main floodplains	>60%	5	There is little difference between population density in 'floodplain' subdistricts compared to those further away from the river (532 persons/km^2 versus 577).	Census of India (2001)
Overall water quality in the basin	Class D	2	The water cannot be used for drinking or bathing, but is still suitable for propagation of wildlife and fisheries. Regular monitoring reveals substantial contamination by human waste as well as mixing of discharges from industrial effluent,mainly from sugar mills.	CPCB (http://www.cpcb.nic.in) Behera (1995)

Protected areas include the Hastinapur Wildlife Sanctuary (2,073 km^2), which hosts the two-toed Barasingha (swamp deer), sambar, cheetal, blue bull, wolf, leopard, hyena and wildcat. Birds on the 'Red List' reported from the sanctuary area are: Greater Spotted Eagle, Swamp Francolin, Sarus Crane and Finn's Weaver. In 2005, the 85 km stretch of the Ganga between Naraura and Brijghat was declared a 'Ramsar Site' due to the WWF's ongoing Gangetic Dolphin Conservation Program. Considering the river reach only (without its catchment), the protected area proportion is, therefore, around 30 % of the length, which is well above the IUCN norm of 10 %. This approach has been used here to reiterate the importance of the reach for conservation.

Sensitivity of aquatic ecosystem to flow reduction is very difficult or even impossible to evaluate in the absence of direct relationships between ecosystem and flow changes. The diversion of the flow in the Ganga River has been ongoing since the early 1850s, and riverine ecosystems have gradually adjusted to such diversions with certain losses. However, there have been instances when parts of the river in this reach went dry in the past. This cannot be explained by natural flow variability only, but is rather the cause of diversions. Such events lead to increased stress on the ecosystem, especially on species like the dolphin that need deep pools of water and high flow velocities (Behera 1995). Das et al. (2005) has analyzed the impacts of irregular water flow from barrages on the river dolphin population and found that the reduced dolphin numbers correlated with the reduced downstream flow, in the study stretch.

Other scientists have identified reduced river flows as one of the primary threats not only to the populations of dolphins, but also to Mahseer (a local endemic carp group), crocodiles and turtles (Rao 1995); although no quantitative data on this is available.

Since the Gangetic Plains have been inhabited for centuries, the dominant land-use has been agriculture, which has certainly affected the proportion of natural cover in the basin. According to some recent sources (Revenga et al. 1998), over 80 % of the original forest cover in the entire Ganga basin has been lost. However, some areas in the subbasin of the study reach still remain under grasslands (e.g., protected areas like the Hastinapur Sanctuary). Forests have recently started to show a tendency of recovering some of its lost cover (a marginal increase in forest area of 2–5% has been reported in the past decade—Census of India 2001). However, most of the basin is now under agriculture. Similarly, almost the entire floodplain of the Ganga has been converted to agricultural land. The *remaining floodplain areas* range from 1.5 km (at both sides of the river in total) at Haridwar to some 20 km near the Naraura Barrage (estimated using images from http://www.earth.google.com). Less than approximately 10 percent of the original (i.e., 10,000 years ago) floodplains still remain (R. Sinha personal communication).

The degree of flow regulation in the basin is still relatively low. There were no storage reservoirs along the stretch or upstream of it, until the completion of the Tehri Dam in 2005. Nilsson et al. (2005) classify the entire basin, including the main channel and tributaries as 'moderately affected' by regulation. However, four major barrages have been constructed in the study reach from 1850s onwards. Some sources suggest that diversion and regulation in the reach remove approximately 50 % of the discharge compared to 66 % for the entire basin (Payne et al. 2003). This, however, is likely to be significantly overestimated as the data on observed historical flows in the Ganga are not readily available. The barrages fragment the main river into three reaches, resulting in 0.013 structures per km across the flow, which is used here as an estimate of the degree of river fragmentation (Table 1 and 7). Some of the barrages constructed more recently, like the refurbished lower Ganga barrage at Naraura, have fish ladder arrangements that restore connectivity to a limited degree. However, these structures are based on designs for rivers in the temperate zone (Kottelat and Whitten 1996) and, as such, their effectiveness in the tropical rivers is unknown.

Behera (1995) reports over 80 species of fish in the study stretch. A comparison with Menon's (1999) description of freshwater fish in the Ganga basin reveals that about 60 of these species are native. Thus, slightly over 20 % of the fish species recorded in the stretch may be seen as *exotic fish*—including carps and catfishes that may have been introduced for fisheries. At the same time, this may be an overestimation as exotic carp in India are few (V. V. Sugunan, ICAR, New Delhi, pers. comm.). Hence, the above figure needs to be verified in the future.

According to the Census of India (2001), there is little difference in the human population density between areas adjacent to the river and those further away from it (Table 7). The water quality of the study reach is regularly monitored by the Central Pollution Control Board of India (CPCB - http://www.cpcb.nic.in) at Rishikesh, Haridwar, Garhmukteshwar, and Naraura; and occasionally—during research projects (Behera 1995). It varies in different parts of the reach from class B to D with most of it falling into class D, due to contamination of the river by human wastes that exceed the permissible thresholds and high Biochemical Oxygen Demand (BOD) values around Naraura (due to the presence of sugar industries in the area).

In the short-term, the flow downstream of the Tehri Dam is likely to decrease, while the increased use of groundwater for irrigation may reduce the baseflow, especially during summer months. The increasing diversion of river water for irrigation is the single most important consumptive use in the study reach. In addition, the power generation facility of the Tehri Dam will need its peaking power requirement met, which, in turn, will create a pulse discharge into the river downstream that can be felt as far as Rishikesh or even Haridwar. These factors adversely affect the single most important ecological issue in the reach—the protection of the Gangetic Dolphin. Although, due to recent conservation efforts its population has doubled (from 22 to 45) since 1995, the habitat for the dolphin in the Ganga is threatened by irrigation diversions and changes in flow variability. The overall prospects for the dolphins in the country remain a concern with their annual fatality rate nearing 10 %.

Discussion and Conclusions

Once the scores for individual indicators have been estimated, it is possible to calculate their sum and express it as the percentage of the total *maximum possible* sum of all indicators. This percentage may then be converted into the most likely Environmental Management Class (EMC), which, in turn, determines how much water (*environmental flows*) needs to be allocated for environmental purposes in each river basin (Smakhtin and Anputhas 2006). These environmental flows are determined by the modification of the natural (reference) flow duration curves according to the class. Similar to the various number and types of ecological indicators used, various procedures and categories can be proposed on how to use the indicators to establish the EMC, or directly—the environmental flows themselves. In this study, the scores have been divided into six unequal categories, each representing one of the six EMCs described in Table 8. The 'score ranges' in groups are arbitrary, with larger ranges in lower classes C and D.

The rule of thumb has been that rivers/basins in the most natural category (A) are rare and, even if present, may not be assigned to this category due to development needs. The other extremes—classes E and F—should generally not be considered as feasible management options (which stem from the rules adopted in South Africa, e.g., DWAF 1999). Classes B, C and D together, thus cover most of the available range of percentage values (Table 8). This system is clearly arbitrary at present, and a much more extensive research effort as well as further expert discussions are required to justify how to convert the indicator scores into different EMCs.

The final sum of all indicators and the estimation of EMCs for each basin or subbasin are given in Table 9. Most of the basins examined in this study fall into class C, three—into class B and two—into class D. The basins/reaches in the highest class (B) are primarily headwater or 'smallish' basins located/originating in the Western Ghats, with high habitat diversity, species richness and, are relatively less developed compared to basins located further downstream. This combination of relatively natural conditions on the one hand, and higher sensitivity/importance due to greater species diversity, etc., on the other, places these basins in a high category. Two subbasins (in this study), placed in the lowest class D, are on the contrary, located in the most downstream parts of the basins. It can also be noted that Lower Krishna, although in class C, is at the lowest boundary of this class (Tables 8 and 9). An interesting example is the Narmada basin: it falls into class C primarily due to its two low scores on rare and unique species (Table 9). This reduces the importance of the basin and makes the otherwise relatively natural basin an 'attractive' candidate for development. But as Table 5 indicates, there are unpublished sources suggesting that rare and unique species do exist in

Table 8. Approximation of Environmental Management Classes (EMC) by total indicator scores.

A sum of actual indicator scores as a percentage of the maximum possible sum	EMC	Most likely ecological condition (adapted from DWAF 1999).	Management Perspective
91–100	A	Natural rivers with minor modification of in-stream and riparian habitat.	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions, etc.) allowed.
75–90	B	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications.	Water supply schemes or irrigation development present and/or allowed.
50–74	C	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present.	Multiple disturbances associated with the need for socioeconomic development, e.g., dams, diversions, habitat modification and reduced water quality.
30–49	D	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail.	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation.
15–29	E	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. Generally, this status should not be acceptable as a management goal. Management interventions are necessary to restore flow pattern and to 'move' a river to a higher management category.
0–14	F	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat andbiota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible.	This status is assumed to be not acceptable from the management perspective. Management interventions are necessary to restore flow pattern, river habitats, etc. (if still possible/feasible)—to 'move' a river to a higher management category.

the Narmada basin, which may raise the scores of these indicators and increase the overall EMC of the Narmada. At the same time, the Periyar basin, which scores high on most of the sensitivity/importance indicators, is in the high class B category despite its low score, due to the presence of multiple dams in the basin. In general, high indicators of sensitivity/importance together with high indicators of the current ecological conditions place a river into a high management class, while any 'loss' of indicator scores—either in terms of current condition or importance/sensitivity—leads to lower EMC and hence, a lower environmental allocation.

Table 9. Calculation of Environmental Management Categories (EMC) for selected study basins based on their indicator scores.

Basin/Reach	Ecological Indicators*													Sum of Indicator Scores	Maximum Possible Sum of Scores	Percent of The Maximum	Probable EMC
	Rare and endangered aquatic biota	Unique aquatic biota	Diversity of aquatic habitats	Presence of protected or pristine areas	Sensitivity of aquatic ecosystem to flow reduction	Percentage of watershed remaining under natural vegetation	Percentage of floodplains remaining under natural vegetation (or % of floodplains remaining)	The degree of flow regulation	Percentage of watershed closed to movement of aquatic biota by structures or degree of flow fragmentation	Percentage of aquatic biota that are exotic	Aquatic species' relative richness	Human population density as % of that in the main floodplains	Overall water quality				
Tungabhadra—headwaters	4	3	4	2		5				5	4		5	32	40	80	B
Tungabhadra—middle	3	1	3	2		3	3			4	5	1	3	28	50	56	C
Tungabhadra—lower	3	1	3	2		2	2			4	3	1	3	24	50	48	D
Krishna—headwaters	2	4	5	1		4				5	3		5	24	40	60	C
Krishna—middle	3	2	4	3		3	3			4	5	3	3	33	50	66	C
Krishna—lower	3	2	2	1		2	2			3	3	4	1	25	50	50	C
Cauvery—headwaters	4	4	5	4		5				5	4		5	36	40	90	B
Cauvery—middle	3	2	3			3	3			4	4	4	3	28	45	62	C
Cauvery—lower	2	1	3	1		1	1	4		4	2	4	2	25	55	45	D
Narmada	1	1	4	5	3	2		5	4	5	3		4	37	55	67	C
Periyar	5	5	5	5	4	3		3	1	3	5		4	43	55	78	B
Ganga (Rishikesh–Naraurareach)	4	4	3	5	3	2	1	4	3	1	5	5	2	42	65	65	C

Note: * Some indicators have not been calculated in individual river basins either because they were not applicable (e.g., there are no floodplains in most headwater areas and in the Narmada Basin) or due to data limitations

Smakhtin and Anputhas (2006) presented, among others, relationships between EMCs and the amount of natural long-term mean flow at the outlets of major river basins in India. If their relationships are used together with the procedure suggested herein, the environmental water requirements at the outlet of Krishna, for example, would be 18 % of the long-term mean flow; Cauvery around 11 %; Narmada 14 %; and Periyar 28 % of their long-term flows, respectively. It is important to understand that this report introduces the approach rather than the final method for setting EMCs for Indian rivers. Even if the existing EMC setting approach is retained for future management of Indian rivers in principle, it is necessary to be aware of its multiple limitations, including, but not confined to the following:

- The set of indicators used here is very preliminary and the selection of indicators needs to be revisited. Apart from the rather general nature of some indicators, no indicators relating to the social importance of rivers have been considered in the approach, at present. This is acknowledged as a serious limitation and one that needs to be addressed in future work.
- The existing information base for determining any ecological indicator in India is very limited. The authors of this report used their own knowledge of and judgment on specific rivers, but other specialists will need to be involved in estimating the scores to improve the level of confidence in the approach.
- The scale of the analysis was very coarse and a similar or a different set of indicators needs to be used at much smaller scales, e.g., for a particular reach of any river, rather than for arbitrarily selected, big areas of already very large river basins (with Periyar being the only exception).
- There seems to be a lack of agreement on such specifics as how many fish species there are in India as a whole, which, in turn, determines the estimation of several other indicators. There is little knowledge on the diversity of other aquatic species. Uncertainty and lack of information will, however, always be unavoidable factors, and it will be necessary to find ways to handle them generally, in such an approach.
- It is a challenge to bring into account coastal fish diversity to an EMC estimation for a river basin unless, of course, estuarine freshwater requirements are estimated using a protocol different from environmental flow assessment for inland rivers.
- The procedures used in this report to convert the indicator scores into EMC are very arbitrary but illustrative. They are given here primarily to stimulate further development in this field.
- There is currently no system of rating the level of confidence for the indicators and/or overall score. This is typically done with similar approaches, and the one presented herein would benefit from attention to this aspect in future work.
- The estimation methods of individual indicators have varied slightly between the basins, due to varying data availability, specifics of the basin and professional judgment. These differences should be eliminated in the future, and be replaced with a more strict assessment protocol.

- Some indicators, like s*ensitivity of aquatic ecosystem to flow reduction,* are very difficult or even, impossible to evaluate in the absence of direct relationships between ecosystem and flow changes. The above appears to be the most weakly developed indicator and yet a critical one for the entire process. It may need to be replaced by a set of different and more specific indicators in the future. Such indicators may be defined through an expert workshop on indicators (see below).

It should also be noted that although useful, the scoring approach should not be used only for the estimation of EMCs. It may also be applied to estimate the permissible levels of reduction/increase of various flows—directly, as suggested by Smakhtin and Anputhas (2006).

As an immediate follow-up to this preliminary study on ecological scoring, the authors of this report propose to hold a national workshop, which would engage several aquatic ecologists, hydrologists, social scientists, etc. The objective of this exercise would be to design a more reliable assessment methodology of environmental importance and conditions of Indian water bodies.

The authors also consider it important to start the process of ecological status assessment of all Indian water resources—at the fine scale of spatial resolution. This new large-scale program should tap into the already existing ecological expertise in the country, and should redirect it from largely descriptive/inventory type work into the context of quantification of ecological water requirements of Indian rivers and wetlands.

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Groundwater Situation in Urban India: Overview, Opportunities and Challenges

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Introduction

Groundwater is a major source of water and is intensively exploited for private, domestic and industrial uses in many urban centers of the developing world. At the same time, the subsurface has also come to serve as the receptor for much of the urban and industrial wastewater and for solid waste disposal (World Bank 1998). Groundwater plays a fundamental role in shaping the economic and social health of many urban areas. However, no comprehensive statistics exist on the proportion of urban water supply world-wide derived from groundwater. It is estimated that more than 1 billion urban dwellers in Asia and 150 million in Latin America depend directly or indirectly upon well, spring and borehole sources (World Bank 1998a).

A number of factors determine the extent to which a city would depend upon groundwater to meet its water demand. The first set of factors can be called physical/ geographic—availability of sufficient groundwater either from natural recharge due to combination of good rainfall and receptive subsurface geology or from other sources such as canals, good aquifers that can store and transmit groundwater, availability of good quality groundwater that is not subject to constraints such as saline water intrusion. The second set of factors is determined by the ability of the urban area to cope with its water demand from external sources. This is driven by the economic scarcity rather than physical scarcity, or the latter may compound the former. In the event of physical scarcity, cities/ towns will still continue to grow with its buffer capacity. The available empirical evidence suggests that, by and large, cities have been able to obtain supplies, often at a greater cost than is necessary but without significantly compromising their ability to expand and prosper even in the most unhelpful locations (Molle and Berkoff 2006). Hence, water supply to any urban center is determined by its physical characteristics or economic and financial capacity. In the competition for water, cities generally win over agriculture (Molle and Berkoff 2006), but when it comes to competition between two cities or towns the dynamics are very different. Negotiation for water is more difficult for smaller urban centers that have lesser say on the water stored at distant reservoirs. In contrast, the larger urban areas[1] backed by population mass, financial capacity and political influence can attract surface water from distances of hundreds of kilometers. Newly developing urban centers (class-III to class-VI[2]) also have to depend upon their local water resources.

On the overlapping of these two sets of factors, one can arrive at the general level of dependence of urban areas on groundwater and their vulnerability at present and in the future in meeting their water demands from external sources. An accumulation of many such vulnerable urban areas within a small region or within a single river basin also implies an additional stress on water resources in the region and possible diversions of water from other uses such as irrigation or even from other regions. Therefore, one can also envisage such areas as those with high competition in the future between urban and other uses.

How would such patterns of dependence and vulnerability of urban areas to groundwater emerge? One can expect that a dominant factor driving these patterns would be the hydrogeological conditions. In India, the peninsular areas with basaltic and crystalline formations, unsuitable for groundwater exploitation, would exhibit relatively greater dependence on external surface water sources than the northern urban areas over the alluvial belt. On these would be superimposed factors such as local rainfall, location within canal commands, problems of coastal salinity, proximity to reservoirs etc. The peninsular river basins, therefore, on an average would exhibit higher proportion of urban areas depending on surface water than the northern urban areas, which have good access to local groundwater supplies from rich aquifers augmented by natural and canal recharge. But, the rich alluvial aquifers of northern India, where groundwater overexploitation has already taken place by irrigators and/or urban centers, will have to tap new water sources (surface or groundwater) in the near future.

This paper analyzes the impact and effect of ‘supply-based’ urban water management strategies and endeavors to identify, using some assumptions and hypothesis, the urban pockets or regions, which may face problems relating to groundwater and eventually become a black-hole for any imported water in the vicinity in India. Although there are two sets of factors - economical and physical - that mainly govern groundwater use in any urban area, the present study is restricted only to the physical aspects of it.

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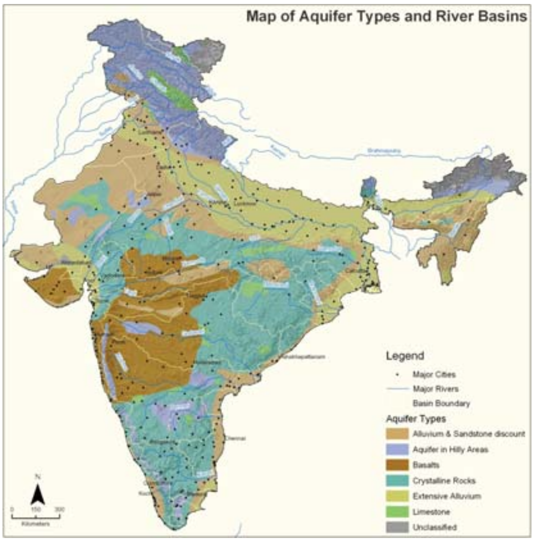
[1] The census of 1961 adopted a two-fold categorization to identify urban centers. First, the settlements that were given urban civic status like corporation, municipality and cantonment by state governments were identified as statutory towns. Second, three demographic criteria were applied to identify the census towns. These were (a) population size of 5,000 or more, (b) density of at least 400 persons per square kilometer, and (c) at least 75 % of the male workers to be engaged outside agriculture (Sivaramakrishnan, Kundu and Singh 2005).

[2] According to the census of India, urban areas are classified into six classes based on population. Class-I = 100,000 and above; Class-II = 50,000 – 99,999; Class-III = 20,000 – 49,999; Class-IV = 10,000 – 19,999; Class-V = 5,000 – 9,999; Class-VI = less than 5,000.

Hypothesis

This paper seeks to enquire a causal relationship between the physical environment and urban groundwater use through a spatial analysis. It is aimed to identify cities already undergoing, or may face in the near future, the physical scarcity of groundwater for use. This physical scarcity of the cities can be determined based on the geographical factors i.e., rainfall and recharge rate, hydrogeology, water deficit or rich river basin, population size, present groundwater utilization within city and its surroundings etc.

Figure 1. Location of urban centers (taken for the study) on the aquifer and basin map of India.



Methodology

The study is based on secondary data. The main data used here for the analysis is from a recent study conducted by the National Institute of Urban Affairs (NIUA), Government of India, which gives the status of water supply and sewerage in more than 300 cities consisting of metropolitan areas, class-I and class-II cities across different states (NIUA 2005). In addition to this, information on urban water for many cities and towns was obtained from various individuals: NGOs' and previous IWMI's studies i.e., total urban water supply, groundwater and surface water supply etc; reports of the Central Ground Water Board (CGWB), Central Water Commission (CWC) and National Commission on Integrated Water Resources Development (NCIWRD). The census of India and irrigation census have also been used as auxiliary information.

About NIUA Study

A questionnaire-based survey of 304 cities and the urban authorities was conducted by the National Institute of Urban Affairs, Union Ministry of Urban Development (NIUA 2005) during 1999 to 2002 and the report was published in 2006. The study encompassed 22 mega-cities, 164 class-I cities and 117 class-II cities. The data collected pertains to the quantum of water supply, groundwater and surface water supply, sources of water supply, standards adopted by urban water supply, water supply duration, demand-supply and deficit etc. The data of urban centers was superimposed on GIS layers of river basins, aquifers, district groundwater situation (CGWB 2004) etc. (Figure 1).

Findings and Discussion

Hydrogeology

Subsurface geology beneath the urban areas plays a key role for the dependence on groundwater. The alluvium plains bestowed with water-rich aquifers and/or with high groundwater recharge either naturally owing to good rainfall or from canals, support urban centers through high groundwater potential. Urban centers situated above crystalline rock or basalt will not be able to support groundwater development, due to its subsurface storage limitations. For example, urban centers in southern peninsular India are heavily dependent upon surface water, as scope for groundwater development is limited owing to hydrogeological conditions.

Out of the total water supply, the proportion of surface water (SW) in the urban centers above hard rock geology such as basalt, crystalline rocks and limestone, was 92 %, 79 %and 95 %, respectively (Table 1). These three regions cover 15 %, 30 % and 3 %, respectively of total geographical area of the country. The total available storage of groundwater bodies in hard-rock aquifers is strictly limited by their weathering characteristics and water-bearing properties. These aquifer systems (which comprise principally such formations as the weathered granitic basement complex and the Deccan Trap Basalts and occur largely outside the major irrigation canal commands) are the worst affected in terms of resource depletion (Foster and Garduño 2007). Such subsurface can barely support smaller towns (class IV to VI) with its groundwater resources. Hence, larger the city in such a region the more would be the dependence on surface water. Interestingly, basaltic hard-rock region has the highest urban population. Any additional urban growth will have to be supported by reallocating the irrigation

Table 1. Relationship between aquifer and surface water supply.

Aquifers	No. of sample cities	Average of % of SW supply in urban centers	% Urban population **
Alluvium and Sandstone discourse	78	55.90	27.50 %
Aquifer in Hilly Areas	19	52.66	28.28 %
Basalt	43	91.77	39.56 %
Crystalline Rocks	70	78.90	28.22 %
Extensive Alluvium	84	25.16	21.93 %
Limestone	2	94.89	23.70 %
Overall	296	57.88	27.33 %

Source: Based on NIUA, 2005 data; ** Based on Census of India 2001 water. This means that SW irrigation will be under constant pressure from the urban growth which and irrigation in these regions will have to improve water use efficiency.

River Basins

River basin wise water utilization in agriculture, domestic and industrial uses as well as rural drinking water has been analyzed in Amarasinghe et al. 2005. We have used CGWB 2004 data for the analysis (Table 2).

Table 2. Basin-wise groundwater (GW) supply in a percentage.

Basin	No. of sample cities	Ave. % of GW supply in cities	% Urban population **
Barak	5	11.34	Not available
Brahmani_Baitarn	3	66.67	13.73 %
Brahmaputra	5	21.82	14.38 %
Cauvery	17	7.35	38.08 %
EFR1	7	22.02	20.96 %
EFR2	18	22.20	46.57 %
Ganga	109	66.94	22.48 %
Godavari	18	5.37	25.66 %
Indus	21	66.46	28.48 %
Krishna	26	14.39	33.07 %
Luni	16	35.83	31.42 %
Mahanadi	5	27.55	20.29 %
Mahi	4	50.74	18.25 %
Narmada	5	28.21	28.94 %
Pennar	8	47.62	23.92 %
Sabarmati	3	40.93	36.37 %
Tapi	5	0.00	34.12 %
WFR	21	19.05	47.17 %
Total	296	41.10	27.33 %

Source: Based on NIUA, 2005 data; ** Based on Census of India, 2001

Note: EFR1: Easterly flowing rivers between Mahanadi and Pennar; EFR2: Easterly flowing rivers between Pennar and Kannyakumari; WFR: all westerly flowing rivers i.e., Kutch, Saurashtra, between Tapi and Tadri, Tadri and Kannyakumari

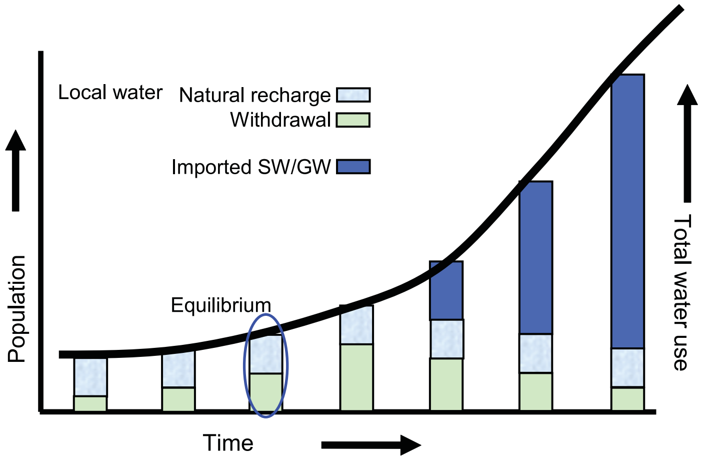
Looking at the basin-wise GW supply of the urban centers, Ganga, Brahmani-Baitarn and Indus have the highest proportion of GW supply - more than 66 %. Among sample cities, Tapi River basin has no GW supply, while, Mahi, Pennar and Sabarmati also have GW supply above 40 %. Groundwater supply also depends on the aquifer. Several river basins such as Krishna, Godavari, Cauvery and EFR2, in which major part of urban water supply comes from surface water, also have relatively high urbanization. Sabarmati and Luni have high urbanization and also high dependence on groundwater.

Groundwater Dependence Versus Population of the City

The size of the city is a strong indicator of how much surface water it can import or how much it has to rely on local sources of water. Urban centers with a larger population have more negotiating power for the quantity of water needed. In India, 56 % of metropolitan, class-I and class-II cities are dependant on groundwater either fully or partially (NIUA 2005). Towns smaller than this mostly do not have access to imported water (mostly surface water from the nearby reservoirs). Hence, overall dependence on groundwater for urban water supply in India is very high. Larger urban spots (million plus cities) on the Indian map are growing rapidly. But, many small spots (class-I and class-II cities) are emerging on the map, at a rate much faster than the million plus cities (Mahmood and Kundu 2004). Day by day, the dependence of urban authorities on groundwater within the city limits and from surrounding areas has been on the rise (Londhe et al. 2004; Phansalkar et al. 2005). There has been a rise in private tubewells within the city as well as tankers supplying drinking water to urban areas.

If we plot population growth with time and urban water supply of any city, it can be seen that, initially, there will be higher dependence on local water resources i.e., water bodies, tapping shallow aquifers using dug wells etc. As population grows, local water resources may no longer be able to fulfill the needs and hence, as a result, chase for declining groundwater levels increases using bore-wells and tubewells. That is where the city crosses the equilibrium (column three from left to right in Figure 2). As urban centers continue to grow, the volume and proportion of imported water increases and water supplies that were originally obtained from shallow unconfined aquifers may no longer be sufficient, because (a) the city outgrows the supply capacity of the local aquifer; (b) often quality, especially of GW deteriorates. Hence, if the local water sources are insufficient in quantity and/or quality for urban domestic use, the city needs to import water from beyond its urban limits (World Bank 1998a; World Bank 2003). Once a city manages to get assured water supply from external sources, it gradually abandons or reduces the local water resources. Eventually, city's claim for external sources becomes stronger and larger (last three columns in Figure 2).

Figure 2. Hypothetical plot—population growth with time versus water supply.

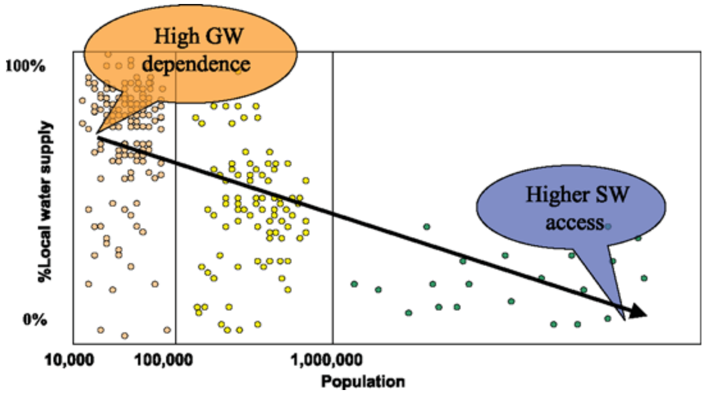


Thus, importing of water becomes inevitable for any city if it continues to grow. The time may vary from city to city depending upon the availability of local water resources in terms of quality and quantity. If this does not happen, then the city's development may get smothered. For instance, Ahmedabad had started importing water since 1980 and it has kept on increasing; Kolkatta is a classic example. Perennial Hugli River is a continuous source for groundwater recharge. Hence, theoretically, using GW for urban water supply seems to be the most practical option. According to CGWB (Rainwater Harvesting Dossiers, CSE, Undated), due to GW mining[3] Kolkatta is on a 'highway' to disaster. Total groundwater extraction is 1,123 MLD against the safe yield of 204 MLD, which has resulted in land subsidence in many parts of the city. Hence, the city is now forced to import water (SW or GW) beyond its urban limits.

Now, if we plot many urban centers, based on the population size and source of water supply, we find that larger the population size of urban centers the lesser would be the dependence on local water supplies. As towns transform into cities and mega-cities dependence on external sources of water increases.

Figure 3 shows the hypothetical lay out of the population size of urban centers versus dependence on local water resources. Based on this hypothesis we plotted around 315 cities (based on NIUA 2005 and other individual studies) and the result is shown in Figure 4. Among higher groundwater dependent million plus cities, Jaipur fetches nearly 90 % of its total urban water supply from a groundwater reservoir that is around 100 kilometers away. Ludhiana in Punjab receives all its urban water supply from the groundwater reserves. The city, at present is sustaining on its economic capacity. District level groundwater development is 144 % (CGWB 2004).

Figure 3. Hypothetical plot - population size versus dependence on local water resources.



Correlation between the size of city and its dependence on groundwater is indicated in Table 3. Average dependence of the urban centers on groundwater covered under NIUA 2005 study shows that it increases from 12 % to 36 % to 49 % with the decrease in city size from mega-cities (one million plus) to class I cities to class II towns.

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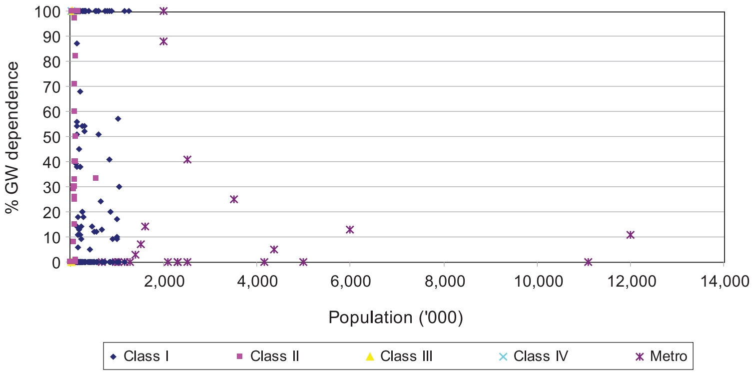
[3] GW mining – when groundwater withdrawal increases the recharge.

Figure 4. Groundwater dependence versus city/town's population.



Source: Based on NIUA study (2005) and other individual studies

Table 3. Percentage water drawn from surface and ground sources – 1999.

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

Source: Based on NIUA study 2005

It should be noted that, these figures are for the water supplied by urban authorities and not the actual use. Proportion of informal water supply is higher in smaller towns than in the bigger cities (NIUA 2005 and personal observation during IWMI's field work). The coverage of urban water supply system was found to be 98 %, 91 % and 89 % in million plus cities, class-I and class-II, respectively. It is a commonly observed phenomenon that population not covered in the formal water supply system often depends upon groundwater i.e., individual dug-wells, borewells, tubewells, hand-pumps, tankers from peri-urban areas etc. For instance, in the year 2004, Chennai wastewater generation was three to four times the piped water production, and in May of the same year, when the Metro Water Board could not distribute piped water at all, 11,000 tankers were crisscrossing the city to provide minimum quantities of water to households and businesses. These coping strategies have obvious physical and environmental limits, as the water is supplied from a large aquifer outside the city (World Bank 2006). For larger cities, such cases are documented but for the smaller towns it is a routine. Hence, dependence on groundwater would be much higher than the plot shows. Similarly, coverage of water supply does not necessarily mean adequate water supply. According to NIUA 2005, average water supply was found to be 182 liters per capita per day (LPCD), 124 LPCD and 83 LPCD in million plus cities, class-I and class-II towns. Thus, undersupplied quantity of water is managed from the groundwater sources (Table 4).

Table 4. Share of ground and surface water source – 1999 (no. of cities/towns).

Size class of urban centers	Only SW		Only GW		SW and GW				Data not available		Total	
					SW <50 %		SW>50 %					
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Metros	12	55	1	4	2	9	7	32	0	0	22	100
Class I	69	42	54	33	10	6	30	18	1	1	164	100
Class II	49	43	48	42	4	3	13	11	1	1	115	100
Total	130	43	103	34	16	5	50	17	2	1	301	100

Source: NIUA study 2005

Notes: SW = Surface Water, GW = Groundwater

However, the overall dependence of these urban areas on groundwater for their water needs as compared with surface water sources shows wide variation across the country. Which type of cities shows greater dependence on groundwater? On a general basis, larger cities have easier access to surface water sources from lakes or from reservoirs located possibly far away from the city limits e.g., New Delhi, Ahmedabad, Mumbai, Bangalore. However, this is not true for the smaller cities which have high to full dependence on groundwater resources unless they have nearby sources of surface water e.g., Anand, Kolar, Barabanki (Anand et al. 2005; Raju et al. 2004). As mentioned, these smaller towns (class-I and class-II) in India are showing maximum growth in population as compared with both million plus cities and the new smaller towns (class-IV to class-VI). The degree of vulnerability of these high-groundwater dependant cities varies with geographical and hydrologic factors, on the nature of local groundwater resources available and alternative use for that. In the regions where there is already a high level of groundwater development from irrigation, groundwater-starved cities will/are pose(ing) competition in respect of irrigation, for example northern and western Rajasthan, North Gujarat etc. High competition can impose a limit on growth on both irrigation and urban development in these areas unless there is better management of the local groundwater resources. In addition to this, many of these locations are surrounded by high industrial polluting units, which degrade the quality of groundwater apart from existing contaminants. In the context of possible interbasin transfer of waters, these high-groundwater starved urban centers would claim their strong candidature on the arriving water. There is a potential question of allocation of imported surface water between the highly groundwater exploited agricultural areas and developing urban centers. This aspect of urban dependence on groundwater and increasing need for further water is an important aspect to be kept in mind before developing water management at the basin level.

Groundwater Quality and Degree of Development

Groundwater quality can easily be deteriorated by industrial effluents, urban wastewater, overuse of pesticides by irrigators, and seawater intrusion either directly from casual disposal or indirectly as seepage from treatment lagoons or infiltration from surface watercourses or canals. Another potential water quality threat is sedimentary formation, from which water is tapped, which varies over a wide range depending on adjacent rock types and mineral compositions of rocks. Often overexploitation of groundwater magnifies inherent salts i.e., TDS, fluorides and chlorides. Such factors greatly influence groundwater use. For example, in many cities/towns of north, central and south Gujarat (due to inherent salinity) and coastal Saurashtra (due to seawater intrusion and also inherent salinity) many households have installed water treatment plants at individual or community level for drinking water use. For those who cannot afford/manage to install have negative health impacts. (Indu, Sunderrajan and Shah 2006).

Importance of Wastewater and Storm Water in Urban Areas

According to the World Bank 1998, out of the new water any water supply project introduced in the urban areas, around 90 % subsequently becomes wastewater, which must be collected, treated and disposed of in an environmentally sound manner. It has become apparent that common wastewater handling and reuse practices (which are frequently uncontrolled and unplanned) generate high rates of infiltration to underlying aquifers, especially in sandy alluvium. Thus, for smaller towns, where reliance on groundwater is higher, incidental infiltration of wastewater often gives volumetrically the most significant quantities for local ‘reuse’ which is rarely planned and may not even be recognized (Foster et al. 2006). You can potentially improve wastewater quality and store it for future use or else it can also pollute aquifers used for potable water supply. For example, cities’ subsurface with sandy alluvium (Gujarat, Rajasthan, Haryana, Punjab etc.,) where the water table is very deep, on-site sewerage (dry-toilet, composting toilet, cesspool, septic tank and subsurface infiltration, soak pits/wells/ponds, treatment/recharge lagoons etc.,) or sewerage pipes with perforation can be a good option for (a) groundwater recharge and (b) reducing the cost of wastewater disposal and treatment, for example, Kolkata wetland management (KMC). On the contrary, cities in alluvium of Gangetic Basin i.e., UP, Bihar, West Bengal etc., with very shallow water levels should have good a sewerage system with ideally no leakage to avoid any GW contamination. Hence, a better sewerage system is a prerequisite for the sustainable use of GW in the cities of these regions. For cities with lined sewerage network, properly treated urban wastewater can be reused for irrigation and/or by industries as well, as it can become a very good source for aquifer recharge. Hence, wastewater, could then serve as a ‘new’ source of water (Biswas 2006).

Similarly, storm water drainage arrangement in conjunction with the ground conditions and rainfall regime provides a good source of recharge. Where the subsoil infiltration capacity is adequate, the ground is the most economical receptor for urban runoff, thereby avoiding the need for costly surface drainage measures (World Bank 1998a).

This area has major implications in terms of future approaches to groundwater and wastewater management in many rapidly-developing urban centers (World Bank 2003). Provision of urban water supply, even if it becomes universal by 2015 as per the Millennium Development Goals, will not be sustainable by itself unless adequate arrangements are made for wastewater collection, treatment and disposal (Biswas 2006).

Urbanization and Water Management

Urbanization in India

It should also be noted that, it is not only that urbanization is taking place in great magnitude in class-I cities[4], but, the urban centers are also increasing in terms of absolute numbers. Strategically for the water sector, these towns are important for the investment point of view. Most of the class-I and class-II cities face day-to-day problems of financial crunch, low returns on investments, inadequate operating and maintenance expertise and poor civic and infrastructure facilities. Such urban authorities also need reform (World Bank 1998b). Per capita water demand for class-I cities increases dramatically by almost 1.5 times compared with other smaller class cities from 150 LPCD to 220 LPCD (NCIWRD 1999).

Urban Agglomeration

Another important stand-out in urbanization is the increasing trend of 'megalopolis' or 'sub-urbanism'. The cities tend to sprawl. The second cadres of the cities are coming up around the mega-cities. The reason is high prices in the urban core and traditional suburbs drive people to distant suburbs. This pattern owes largely to the preference of middle and the working classes for privacy and space, while elites crave for better living environment which encourages urban sprawl. For corporates, it is taxes that force to keep their godowns and other commercial activities outside municipal limits. In fact, the new sub-urbanism seeks not to fight market forces, but to address the problems. These are not mere bedroom communities with malls, but boast well-developed business parks, town centers and in many cases notably, large amount of well-preserved or developed natural open spaces. Majority of these sprawls are now turning into 'garden cities'. For instance, around Delhi there are peripheral cities emerging to solve all the requirements of the big cities. One key that becomes crucial in this regard is the excellent transportation, which is also argued by Faroohar 2006. Burgeoning IT hubs outside Delhi like Gurgaon, Noida and Gaziabad serve as new bedroom communities and all sit on good roads into the capital. More examples are Virar, Vashi (Navi Mumbai), Pune for Mumbai, Bopal, Vejalpur, Science city for Ahmedabad. Most of these peripheral or second cities depend heavily on groundwater. These cities are normally not covered under municipal corporations, especially for the provision of water supply and sewerage infrastructure. That is why it is very important that these second cities or urban agglomerations need to be covered under urban water supply schemes. Recent amendment in Jawaharlal Nehru National Urban Renewal Mission (GOI 2006) for inclusion of city's peri-urban areas, out growths and urban corridors and other peripheral areas is a step towards addressing the issue.

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[4] Proportion of total urban population of class-1 has increased from 22 % % in 1901 to 60 % % in 2001 (*Source:* Registrar General and Census Commissioner 1993; Indiastat.com 2006; Mahemood and Kundu 2005).

Linkage Between Urbanization, Infrastructure Development, Tourism and Water

With the increase in urbanization and with better infrastructure facilities i.e., roads, electricity, communication etc., tourism activities shoot up. New trend of buying properties for the vacations and holidays in near by hill-stations, lake side etc., is emerging among urban elites. For, example, domestic tourists from Delhi visiting Mussourie, Shimla, Haridwar increase during weekends; Similarly mountains Abu and Udaipur for Ahmedabad; Lonawala, Khandala for Mumbai and Pune elites. Such tourist destinations are increasing in number. Many of such tourist towns are witnessing unexpected growth and unable to cope with water demand from their local water resources. Often tourist destinations are located in geographically adverse conditions. In spite of that, such towns can become black-holes to attract water from distant sources.

Future Work and Conclusion

Methodology for Vulnerability Analysis

What we have presented in this paper is the current status and potential threat of groundwater use in urban centers of India and our conceptual picture of how different geographical factors contribute to vulnerability in terms of urban groundwater. In this section, we outline a proposed procedure to evaluate this vulnerability based on various factors. This methodology utilizes data that is mostly available, but some need to be generated as well. The important factors are: (a) level of current dependence on groundwater for overall urban water use; (b) level of groundwater development in surrounding block/district; (c) average distance to external sources of water; (d) level of development of river basin; and (e) hydrogeological factors e.g., specific yield. A combination of these factors will enable us to identify the current hotspots and future attractors of excess or imported water in any river basin. Some examples follow:

1. Bharuch is a class-I city in Gujarat which uses 90 % of surface water since the local groundwater is overexploited and contains a high concentration of saline. In the surrounding districts groundwater development is around 50 % (source: 2004 Groundwater statistics of CGWB), but it lies within Narmada and Mahi river basins which still have water available for supply to the city. In that case, the city is not under further high stress as far as groundwater vulnerability is concerned.

2. Ludhiana is a metropolitan city in Punjab, which completely relies on groundwater sources. The district level groundwater development is 144 % and it lies within the Indus River basin that is almost closed and highly exploited. The groundwater in this city is highly vulnerable to further exploitation and is already suffering from severe pollution from industries.

3. Barielly is a class-I city in Uttar Pradesh, which receives 100 % of its supplies from groundwater. The district level groundwater development is 86 % and it lies within the Ganges Basin. In this case, even though there is a high dependence on groundwater and high degree of groundwater development, perpetual recharge from

canal system that contributes 40 % of the groundwater recharge in this area (source: 2004 Groundwater Statistics of CGWB), means that there is no current high vulnerability of groundwater exploitation in this town.

On a macro-scale we conclude that the level of dependence on groundwater is greater for smaller sized towns, which have lesser power to demand and have lesser economic strength to pay for water sources that are located at distant places. Though, smaller towns with all the adverse conditions would eventually win over other uses for urban water supply. Rajasthan's Indira Gandhi Nahar (IGNP) Canal is a case in point. The proportion of drinking water has increased over time and will continue so. Gradually all the cities, towns as well as villages in northern and western Rajasthan are being covered by IGNP water. We also see a marked difference spatially in dependence on groundwater with the northern urban areas, which are located on rich alluvial aquifers and get good recharge from canals, highly dependant on local groundwater for their overall water usage. On the other hand, peninsular towns in hard-rock regions have lesser opportunity to develop groundwater resources. To sustain the growth they have to depend on external sources. In case of nonavailability of such external sources of water, this can impose a limit to overall growth of the urban areas. Integration of all the factors such as hydrogeological, within or outside canal command area, rainfall and recharge, population size, proximity to water bodies, urban out-growths, and utilization of wastewater would help planners in designing better and sustainable urban water supply and sanitation systems.

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Natural Flows Assessment and Creating Alternative Future Scenarios for Major River Basins of Peninsular India

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Summary

The current study focuses on the six major peninsular basins of India namely, Brahmani-Baitarni, Cauvery, Godavari, Krishna, Mahanadi and Narmada, for estimating natural flows and residual flows under different scenarios to investigate whether ‘surplus’ water is available in these basins and also to assess the limits of utilization of massive water transfers.

The first part of the study uses the recent historical flow and information, about water use and other anthropogenic changes in the water cycle, to establish a monthly ‘Natural Flows’ series for the basin. This is done by using a simple hydrologic model of the land phase, incorporating a linear groundwater reservoir, and incorporating the anthropogenic changes. The concept of natural flows is being used as a ‘peg’ while proceeding from the current condition to the likely future condition.

The second part, aims to assess the likely future alternate water situation and process the monthly time series of natural flows as established in the first part. The objective was to test the ability of the basin to support alternative possible development scenarios, while maintaining an acceptable level of residual flows. Therefore, different alternate development scenarios are worked out and incorporated in the model. The operation of the reservoir capacity is adjusted, to ensure the availability of a positive, or, if necessary, ‘above a threshold’ flow. Simultaneously, the water use is increased to a level where sustaining the use and maintaining the residual flows becomes impossible, and failures occur in some years. By adjusting the incidence of the failures (in meeting the specified demands) to an acceptable level, the ‘limit of water use’ under the scenario is established. The ‘limits of utilization’ is determined not only by natural flows and the engineering-agronomic constraints, but also by the manner in which the utilization is achieved, including the environmental constraints. Thus, according to the authors, a simple concept of a fixed ‘utilizable flow’ is inadequate.

The analysis was to be done for the hydrologic and developmental environments as expected in the year 2025. The natural flows as would occur in that year, as well as the initial conditions (the storage available at the beginning of the year) cannot be known. Since a series of natural flows for about 15 years (as established in the first part) was available, the analysis

was done for these years by holding the development level as stationary. This allows the depiction of the role of 'over the year' storages in dealing with the good and bad sequences of flows. For all the peninsular basins, covered in the study, the 'business as usual' condition was tested for 'low development' (completion of storage facilities under construction) and 'high development' (taking up and completing additional contemplated storage facilities), without any emphasis on any improved water management. In addition, tests were also conducted in scenarios in which the water management was improved by reducing waterlogging through improved drainage and its reuse (the WM-2 scenario), and also by efficiency improvement and large adoption of micro-irrigation techniques (WM scenario). Two additional environmental-friendly variants of the WM scenario in which a minimum 'low flow' is maintained throughout (EFR-Low scenario), and in which sizeable floods are also maintained (EFR L & H scenario) were also tested.

The study has brought out that considerable dependable surplus flows are available under all future scenarios in the Brahmani-Baitarni, Godavari, and Mahanadi basins, even after considering the current and committed imports and exports. These surpluses could be mopped up in planning the larger interbasin water transfers. The average annual natural flows, as established in the study, are shown in Table 1.

Table 1. Flows in 10^9 m^3 per year.

Basin	Brahmani-Baitarni	Cauvery	Godavari	Krishna	Mahanadi	Narmada
Average annual observed Flow	31.0	14.9	80.3	19.9	58.3	34.6
Average annual estimated natural flow	36.9	25.4	122.1	74.0	74.1	46.7

The uses, as projected for 2025, in regard to the domestic and industrial use, which were comparatively smaller, were not varied across the scenarios. The differences among scenarios were mainly in the agricultural uses and in the environmental flow requirements. The agriculture uses were limited, but were relevant because of the availability of the 'culturable land', the impracticability of irrigating the entire culturable land including high plateaus, and because of the limits imposed by cropping calendars on land occupancy. Table 2 illustrates the information of the limits of possible net irrigation areas (million hectares).

The maximum NIA possible indicates the physical limit imposed by land availability alone, without considering the constraints imposed by the available water. While considering the constraint on the land for agriculture, the impracticability of irrigating all the land including the high plateaus has been considered. The water availability constraint is considered later, through the modeling process as shown in the other columns.

The 75 % dependable surplus flows as available from the basin under the projected uses, is 16.03 $*10^9$ m^3 in Brahmani-Baitarni Basin, 14.55$*10^9$ m^3 in Godavari Basin and 19.19 $*10^9$ m^3 in Mahanadi Basin under WM-scenario. Thus, the study has brought out that considerable dependable surplus flows are available under all future scenarios in the Brahmani-Baitarni, Godavari, and Mahanadi basins, even after considering the current and committed imports

Table 2. Limits of possible net irrigation areas (NIA), in different scenarios (NIA in million hectares).

River basin	Present NIA possible	Maximum	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	1.27	1.74	1.71	1.71	1.71	1.71	1.71	1.71
Cauvery	2.27	3.78	3.37	3.40	3.75	3.75	3.62	3.45
Godavari	5.35	12.43	8.70	10.53	11.75	10.40	11.60	10.61
Krishna	3.31	13.94	4.76	5.25	6.92	6.08	6.35	4.98
Mahanadi	2.46	5.9	3.82	4.06	5.79	5.05	5.79	5.79
Narmada	1.94	4.08	2.95	2.95	2.95	2.95	2.95	2.95

and exports. These surpluses could be mopped up in planning the larger interbasin water transfers (Annexure 1 shows the flow duration curve).

The detailed results including the variable ‘limits of utilization’ across the scenarios, for the various concepts ‘utilizations’ are presented in the text. The main messages flowing out of the study are as follows.

1. In any water situation assessment, the concept of ‘utilization’ needs to be defined, and used consistently. The definition could be based on ‘withdrawals’ from the natural waters, the ‘evaporation- transpiration’, or any other factor. The quantum of the ‘returns’, and the possibilities of their use, and the quantum of the ‘inadvertent’ evaporation-transpiration also need to be assessed.
2. The concept of ‘maximum possible utilization’ for a basin is not good enough. It needs to be replaced by the concept of ‘limit of utilization’ under a specified set of possible actions and constraints.
3. In assessing future situations, a scenario building approach allows the investigation of these limits under alternate sets of actions and constraints; and thus aids in policy formulation.
4. In regard to agricultural water use through irrigation, the in-basin land availability and the limits on irrigated crop occupancy, and the practicability of trans-basin imports and exports, when considered together, would allow an assessment of the limits of utilization, as also the possibilities of additional interbasin water transfers.
5. In water-stressed basins, the ‘business as usual’ strategies are not sustainable. In basins with better water endowments, significant surplus waters would continue to be available, and these could perhaps be transferred.

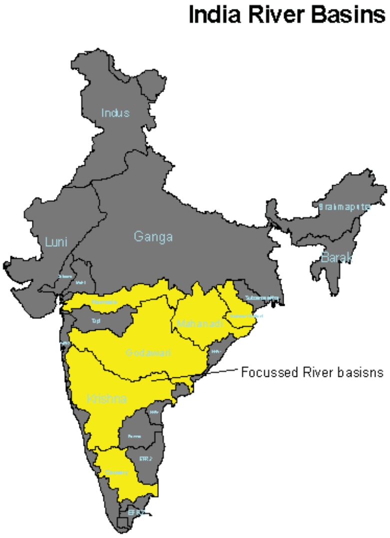
Introduction

India covers 2.4 % of the worlds land area. The fluvial water resources of India ($1953*10^6 m^3$) per year (Central Water Commission) are around 4.6 % of the global resource, whereas it supports 16 % of the world population. The distribution of water resources in the country shows variation over space and time. Over 80-90 % of the runoff in Indian rivers occurs in 4 months of the year, and there are regions of harmful abundance and acute scarcity (NCIWRD 1999). Managing the available water resources would be a great challenge for the country. Large consumptive use of waters, mostly for irrigation, both from the surface and the ground, is a distinctive feature of Indian water situation. The annual utilizable surface water and groundwater is estimated to be 690 km^3 and 432 km^3. (Amarasinghe et al. 2005). Future water management strategies rely both on in basin development and on large interbasin transfers.

This study[1] was undertaken for creating information that could be used in a later analysis of the proposed Indian strategy of large-scale interbasin water transfers. The immediate purposes were to demonstrate a methodology for estimating, from the available information, the 'natural' flows (annual, seasonal and monthly surface water and groundwater resources), and to use these for assessing the likely future scenarios, and the residual flows under each of these scenarios. Also, the development potential of the basins or the limits of possible use, through possible in-basin development, under different strategies, were sought to be established. Another purpose was to study how the limits of utilization, in terms of consumptive use, gets affected by the water management strategies. Inter-comparison of future water management strategies was also a purpose, which could support policy formulation. However, choice of a strategy was considered beyond the scope of the study.

The present study focuses on the six peninsular basins, (covering about 30 % of India's area, 29.2 % of its population and 17.6 % of its water resource.) in estimating the limits of utilization. The study covers the Brahmani-Baitarni, Cauvery, Godavari, Krishna, Mahanadi and Narmada basins (Figure 1). The salient features of the river basin are shown in Table 3.

Figure 1. Water resources – river basin-wise, NCIWRD1999.



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[1] The full text of this study is available on IWMI's website.

Table 3. Salient features of river basins studied.

Serial No.	River basins	Area (sq.km)	Percent of India's area	No. of states involved	Basin population (2001) (estimated)		Average annual water resources, (NCIWRD estimates)		Natural water resource per person.
					Thousands	Percent of Indian population	10^9 m^3	Percent of Indian resource	m^3/ person/ year
1	Brahmani-Baitarni	51,882	1.7	3	18,382	1.9	28.48	1.46	1,549
2	Cauvery Basin	87,900	2.7	3	35,097	3.5	21.36	1.09	608
3	Godavari Basin	312,812	9.5	5	85,351	8.6	110.54	5.66	1,295
4	Krishna Basin	258,948	8	3	73,968	7.5	69.81	3.57	943
5	Mahanadi Basin	141,589	4.3	4	29,690	3.0	66.88	3.42	2,252
6	Narmada Basin	98,796	3	3	19,144	1.9	45.64	2.34	2,384
Total for basin studied		951,927	29.2		261,632	26.4	342.71	17.55	1,310

The concept of 'an utilizable flow' is, much more complex than it appears to be. There is no uniformity in defining the use. The governmental sources in India, generally, define it in terms of 'withdrawals'. This is, however, less appropriate from a scientific-hydrologic viewpoint in view of the returns. The NCIWRD has realized this and has accounted for the returns while using withdrawals as a yardstick. The scientifically pleasing procedure of defining the use in terms of consumption (that is, the evaporationtranspiration) also does not solve the problem of a part of the return occurring into 'sinks' (or where, because of its quality, it has to be led to a 'sink'), and is not capable of future withdrawal and use.

Methodology

A good approach in the present and future water situation assessment is to model the complete land phase of the hydrologic cycle, through a model capable of depicting the likely future changes in the processes, caused by land use changes. Such an approach, as developed earlier (Gopalkrishnan et al. 2006) could not be followed in the present study in view of the large data requirements of that approach. In the present study, only the anthropogenic changes in the land phase of hydrologic cycle have been modeled and estimated.

The general hydrologic concept used by us is depicted below (Figure 2). This is for the 'Pseudo-Natural condition', under which human interventions through rain-fed agriculture are allowed, but other anthropogenic water cycle interventions through uses, including irrigation use, are not allowed. The hydrologic concept used in the current study under anthropogenically modified state of the basin is shown below (Figure 3).

In the present study therefore:

1. Rather than estimating the utilizable flow directly, broad development scenarios were conceptualized.
2. Scenarios were refined using the model, by adjusting the use (withdrawals) to a level which tests the limits of allowable use under the assumptions and constraints of the scenario. For all the scenarios so refined, we present both the (limiting) withdrawal and consumption (Figure 4).

Figure 2. Hydrologic concept used in the study (natural condition).

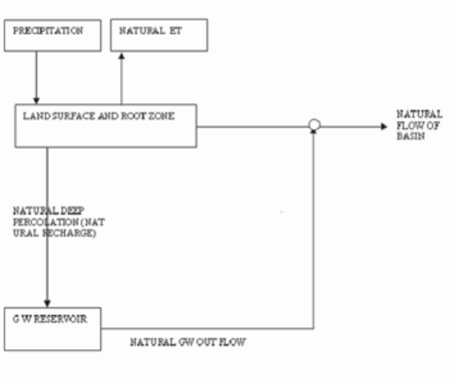


Figure 3. Hydrologic concept used in the study (anthropogenic condition).

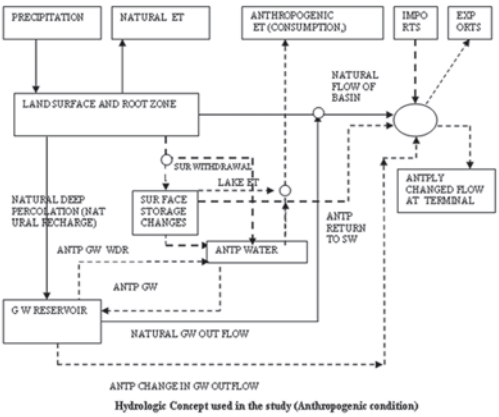
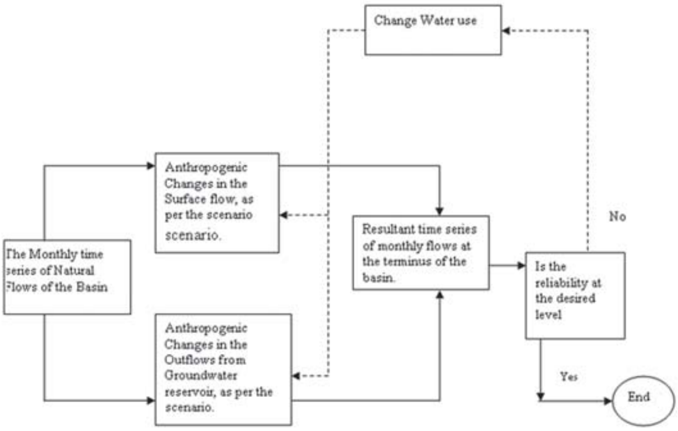


Figure 4. Scheme for refining a conceptual scenario.



Data Availability and Sources

Storage

Information about storage facilities under construction, storage facilities under consideration and ultimate irrigation potential in the basin was taken from CWC's water-related statistics (2004).

Runoff

The observed runoff, at or near the terminal site of the six basins, as a monthly time series from 1989 to 2003 was used in the first part to establish a monthly series of natural flows. In the second part, the natural flows so estimated were used for scenario analysis. For some basins, the series available was for a shorter period.

The period of minimum length data[2] required for assessing the reliability of a plan of development would depend on (i) the interannual variability of hydrologic data and (ii) the predominant type of the development, i.e., runoff of the river, within the year storage and over the year storage. Among the basins studied, the Krishna and Narmada have a predominant storage development with the carry over component as a significant proportion of the total. All other basins have predominantly a 'within the year storage'. Although a 40-year and 25-year long series of monthly flows would have been preferred for a planning exercise, for want of readily available data and in view of the time and resource constraints, the present study was based on a 15-year series.

Land Use and Irrigated Areas

This was obtained from the government statistics. However, a few changes had to be made in two basins, namely Krishna and Godavari, as the data from the government statistics were not consistent with the data obtained from other sources, e.g., remotely sensed data.

Reference Crop Evapotranspiration

The reference evapotranspiration figures for various locations in India and the rainfall figures for these locations were taken from www.iwmi.cgiar.org/WAtlas. Monthly information for 475 locations (districts) of India in regard to the following parameters was available. Penman ET-(minimum, maximum, mean, standard deviation) (mm/day for the month); Precipitation (50 %) (mm/day for the month); Precipitation (75 %) (mm/day for the month); and Moisture Availability Index (mm/day for the month).

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[2] The general Indian practice, in regard to the minimum length of data necessary for project planning is as follows: runoff of the river development -10 years, in weekly or 10 daily time units; within the year storage development - 25 years, in 10 daily or monthly time units; over the year storage development - 40 years, in monthly or seasonal time units.

The following procedure was adopted for analysis purpose,

A. Location-wise analysis

The mean value of the ET_0 (reference crop evapotranspiration) and the mean value of the precipitation (50 %) were chosen. The effective rainfall for the month was estimated from the mean monthly precipitation, using the USDA soil conservation service method. (FAO 1992).

The irrigation water requirements at the field level were calculated for K-crop (crop coefficient) values from 0.5 to 1.1 the location-wise analysis for multiple locations within each basin was important, since the irrigation water requirement computations are non-linear, and at each location, have a lower bound of zero. Lumping of these over a basin would ignore the requirements of those parts of the basin, where the potential evapotranspiration exceeds the effective rain, in situations in which the average requirement is less than the effective rain.

B. Basin-wise analysis

A list of districts which were relevant to each of the basin was prepared. For each month and for each K-crop value, the average irrigation water requirement for the basin was calculated using the list. As an illustration, the irrigation water requirement at the field for the Krishna Basin as a whole, as averaged from the 38 numbers of stations for crop coefficient 0.5 is shown in Table 4.

Table 4. Monthly irrigation water requirements for Krishna (millimeter).

Crop coefficient	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	June-Sept.	Oct-Jan	Feb-May
0.5	61.8	68.7	88.1	82	70.8	11	1.76	1.55	0	3.97	43	56.4	14.3	165	310

The predominant crop and its stage of growth guided the aggregated crop coefficient for any month, over all crops. As explained, the basin-wise aggregation was made after a distributed estimation of irrigation water requirements.

Lake Evaporation

Monthly lake evaporation depths for 19 stations within India (not very evenly distributed) were obtained from Central Water Commission (CWC). Using the data of the appropriate (generally, the nearer) station, and using the estimated lake area, the monthly quantities of reservoir losses (in the historical period) were estimated.

Estimating Total Live Storage Capacity

For major and medium reservoirs, which are the main source of storage facilities, live storage capacity data was readily available (CWC). For minor tanks, the storage capacity was estimated by an approximate analysis, which indicated that for irrigating thousand hectares, a live capacity of 3.5 $*10^{6}$ m^3 would have been built. When building up the future scenarios, the likely loss of capacity due to sedimentation was considered. As per our estimates, the total live capacity of the Indian reservoirs (2003) was 262.87 $*10^9$ m^3, and, the six basins under study had a total live storage of 125.9 $*10^9$ m^3.

Estimating Monthly Live-storages and Lake Areas

Of the total live storage of 125.9 * 10^9 m^3 available in the study area, about 67 $*10^9$ m^3, available in 36 of the comparatively larger reservoirs, is being monitored by the Central Water Commission (CWC). The monthly water level and live capacity information for each of the monitored reservoirs in the six basins were obtained from the CWC and were used to fit a logarithmic reservoir height-capacity curve for each. By differentiating this, a logarithmic area reservoir height-curve was also obtained. In the absence of the readily available data, the values of dead storage and elevation of the reservoir bottom were determined by trials and by using secondary information as available. In general, a very high coefficient of correlation around 0.99 could be achieved through trials. It was also ensured that, in general, the value of exponential in the reservoir height-capacity curve was within the normally acceptable range of 1.5 to 5.

Scenarios

The model built comprised five scenarios, namely BaU-LD; BaU-HD; HD-WM; HD-WM2; EFR-L; and EFR-L&H. None of the scenarios considered massive interbasin transfers beyond those existing at present, which are shown in the table below. The BaU-LD scenario considered a low level of future storage development, whereas other scenarios consider that most of the possible storages would be built by 2025. All the scenarios (except BaU LD and BaU HD) considered a massive drainage improvement to reduce waterlogging, and reuse of the drained water for irrigation as a future strategy. In addition, the HD-WM, EFR L and EFR L&H scenarios considered improvements in surface water distribution efficiency through canal lining etc. The provision of environmental flows in the low-flow season was included in EFR L. Additional environmental flows during the flood period were provided in EFR L & H.

Irrigation Efficiencies and Returns

The irrigation efficiencies (combined conveyance, distribution and application) and the distribution of excess withdrawals, based on the general experience in India, as assumed in the various scenarios, are abstracted below.

The overall surface water irrigation efficiency in the wet season (*kharif*—June-September) was assumed as 0.4 for the BaU conditions and was increased to 0.5 for the scenario with improved distribution. For the other non-wet seasons (*rabi*—Oct-January and hot weather—February-May) the corresponding values were 0.3 and 0.4. For groundwater irrigation, higher efficiencies, ranging from 0.6 to 0.7 (June-October and November-January seasons) and 0.5 to 0.6 for the hot season (February-May) were assumed. Depending on the overall efficiency and irrigation water requirements the withdrawal from the surface or groundwater was computed. The excess of withdrawal over the additional evapotranspirational needs was accounted by dividing it in three parts, namely that lost as additional ET from anthropogenic swamps, that which returns to the surface water system ,and that which returns to the groundwater system. In the BaU scenarios, the distribution ratios were 0.4, 0.15 and 0.45, respectively; whereas in the other scenarios, which involved drainage improvements, the ratios were changed to 0.2, 0.2 and 0.6, respectively.

Domestic and Industrial Uses

The domestic uses depend on the population projections for 2025. For the present, we estimated these as follows. The averages of the 'All India' projections, low and high, as projected by NCIWRD for 2025 were used. These were segregated statewise, and also into rural and urban components. In doing so, the differences in the processes of population growth and urbanization, within the states were considered. The state-wise figures were converted to basin-wise figures, in the proportion of the state areas in each basin. Domestic and industrial uses were calculated by changing the current norms to more reasonable norms for 2025 situation.

The industrial requirements were projected through an approximate but elaborate study, which separately worked out the requirements for 11 types of major industries plus the general small-scale industries. The requirements for each type were partly related to the natural resource distribution and partly to the population growth. An overall increase of more than 400 % for the all India withdrawal figures between 2000 and 2025 was assumed in the BaU type scenarios. In the scenario depicting improved water management, the consumption levels were kept the same as that of BaU type, but with improved water use efficiency, the withdrawal and the return figures were reduced.

The Model Operation, Including the Reservoir Operation

1. The approach was to decide, beforehand, the development parameters of the scenario (storage capacity, imports and exports), the agro-climatologic parameters (ET_0, ETcrop, Effective rainfall), the water management parameters (efficiencies and distribution of excess withdrawals) and also the ecology-related constraints (environmental flows—both low flows and floods), and then to vary the use-related parameters, (target irrigation areas) to estimate the limits of use within the acceptable reliability. Even within the use-related parameters of a scenario, the domestic and industrial uses were held at a prescribed level, and only the irrigated areas were changed in the 'trial and error' procedure for investigating the limits of development. Each basin would be having a large number of major, medium, and minor reservoirs, however, in this generally lumped model of the basin, all reservoirs were lumped into a single reservoir. The approximations involved in such lumping were dealt separately as described in (5) below.
2. The reliability: As per the prevalent Indian practice, the failures in meeting the targets of irrigation, on an annual basis, of less than 25 %, was allowed. The failure percentage, on a crop-year basis was also computed. Irrigation failures were managed by reducing irrigated areas during a failure.
3. The storage facilities were so operated that as much water as possible is held back for future use, after meeting the requirements for uses, and also the requirements for

EFR (Low Flow) and EFR(High Flow) as specified in the scenario. The storage operation was done in a recursive way.

4. Failures were imposed mostly in surface irrigation, and even in these, failures in *rabi* and hot weather were imposed before imposing failures in the subsequent *kharif* and in perennials.

5. The maximum practicable value for the transient storage has the upper bound in terms of the available live capacity, in 2025, under the scenario. However, the limiting storage was assumed to be at 90 % of the live capacity. Similarly, the minimum practicable live storage may not reach the physical bound of zero live capacity. An integrated operation, across political units, may not be fully achieved. Even within a unit, isolated reservoirs may not be operated to cater to deficits much downstream. A small carry-over to cater to a delayed monsoon may be preserved even in the face of a current overall deficit. Considering all these, we kept a small minimum live storage limit of around 1,000 million cubic meters in all scenarios, in the studies. Both these corrections represent an attempt to overcome modeling limitations involved in considering a single lumped reservoir, instead of the distributed reservoirs within the basin.

6. The suggested operational pattern was then used to compute the residual flows for the basin, as also the residual flows at a critical point near the basin outlet. Often, initially, the residual flows included some monthly flow values, which were below the EFR threshold, or were negative. In such cases:

    - Cuts on irrigation areas were applied from the earlier post-monsoon period .Cuts in other seasons were also imposed, if necessary, until the physically impossible negative flows were eliminated. As the hydrologic and storage situation improves with time, beyond the bad run, the cuts in forthcoming seasons become unnecessary.

    - Considering the short period of simulation, it was necessary to leave an ‘end of the period’ storage at a level not far below the average storage for that month. Apart from the number of failures, this became an important consideration.

    - The irrigation area targets were increased or decreased, if the failures were too few or too many, as compared to the criterion of 75 % annual reliability of irrigation. . An account of the cuts, as imposed, was kept, to work out the reliability.

    - The ‘critical point’: All balances were done for the basin as a whole. However, the availability of non-negative (or above threshold) flows at the basin outlet does not imply such conditions at all places in the upstream. Balances had to be worked out at one or more points which may be critical from the water depletion considerations. The decision about which point is to be considered as ‘critical’ would require some knowledge of the basin. For most studied basins, the withdrawal-related stresses occur in the middle and lower portions, since upper parts are comparatively wet, and have less withdrawal. Hence, critical conditions would be occurring at points downstream of the last large withdrawal, and balances at such points were worked out.

Environmental Flows

The environmental flows, as used, were more for demonstration, and a qualitative depiction. No scientific studies based on the ecologically desirable hydrologic regime were available. In the two scenarios, EFR-Low and EFR-L&H, an environmental flow corresponding to about 10 % of the lowest average monthly flow was provided as the low flow which needs to prevail throughout. In addition, a high season EFR that caters to maintain the flood regime of the river to a limited extent, and thereby maintain the geomorphology of the river is also provided for, in the EFR-L&H scenario. The total volume of this High Flow EFR in all wet months in a year was kept at 40 % of the maximum of the average monthly flows. Environmental flows, as used for the various basins are shown in Table 5.

Table 5. Monthly environmental flows, $10^6 m^3$.

Basin	Brahmani-Baitarni	Cauvery	Godavari	Krishna	Mahanadi	Narmada
EFR-L in all months	68	49	150	106	66	49
EFR-L and H (Increased flow in July-Sep, were relevant)	1,157	644	4,915	2,704	3,558	2,134

Results

Natural Flows and Residual Flows

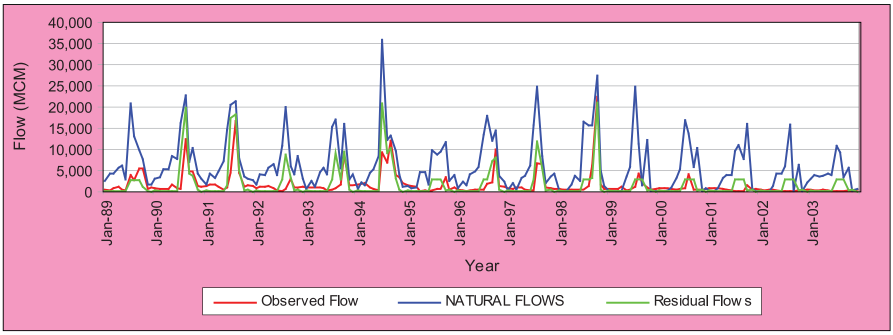
The natural flow series was combined with the expected 2025 development condition under different scenarios to work out the likely flows available at the critical point. The residual flows were worked out after considering the environmental flow requirement as also the needs for reducing utilization by inducing failures of an acceptable nature, in the low-flow years. The results in terms of averages are shown below (Table 6).

Table 6. Observed, natural and residual flows estimated.

Basins	Observed flows, average (1990-2004), 10^9 m^3			Estimated natural flows, average, 10^9 m^3			Estimated residual flows, average,(EFR-L and H) 10^9 m^3		
	Monsoon	Non-monsoon	Total	Monsoon	Non-monsoon	Total	Monsoon	Non-monsoon	Total
Brahmani-Baitarni	20	11	31	26	11	37	17	4	21
Cauvery	6	6	12	13	15	28	2	2	4
Godavari	62	18	80	90	32	122	41	9	50
Krishna	9	10	19	45	29	74	17	5	22
Mahanadi	44	14	58	53	21	74	30	7	37
Narmada	26	8	34	36	10	46	13	3	16

As an illustration, depicting the monthly variability, the estimated natural flow and the estimates of the residual flows under the EFR-L&H scenario for the development condition of 2025 in regard to the Krishna Basin is shown in Figure 5. Similar comparison, under the EFR-L&H scenario for other basins were also carried out.

Figure 5. Comparison of observed, natural and residual flows (EFR-L&H) (2025 condition), $10^6 m^3$, Krishna Basin.



Limits of Utilization

Limits on Land Utilization**:** In Indian river basins where water utilization is largely linked to agricultural development and utilization of the land resources, the limits of utilization can flow out of either the land resources available in the basin or the water-related endowments of the basin. The basin-wise constraints are depicted in Table 7.

Table 7. Constraints on net irrigated area (NIA) (Mha) as used in the study.

Basin	Present			Max possible NSA in 2025*	Unavoidable rain-fed area++	Max possible NIA in 2025+
	Culturable area	NSA	NIA			
Brahmani-Baitarni	2.00	1.94	1.27	1.94	0.20	1.74
Cauvery	5.22	4.07	2.27	4.18	0.40	3.78
Godavari	18.04	14.39	5.35	14.43	2.00	12.43
Krishna	19.29	13.19	3.31	15.44	1.50	13.94
Mahanadi	8.37	5.98	2.46	6.70	0.80	5.90
Narmada	5.00	4.68	1.94	4.68	0.60	4.08

Notes: * Max possible NSA in 2025 was calculated as the Max of the present NSA and 80 % of the culturable area

++ Unavoidable rain-fed area, figures are based on the impracticability of irrigating the high plateau and cutup lands devoid of groundwater and, are not related to water availability constraints

\+ Max possible NIA in 2025, as shown in this table represents the physical upper limit, without considering the constraints imposed by water availability

The Limits on Water Utilization:

The limits of utilization in terms of withdrawals for in-basin use, in-basin consumption and in-basin useful consumption for the six basins for all the scenarios are presented in Table 8.

Table 8. Limits of annual utilization – 2025 (10^9m^3).

	Basin	Brahmani-Baitarni	Cauvery	Godavari	Krishna	Mahanadi	Narmada
BaU-LD	As withdrawal for ‘in-basin’ use	20.3	41.0	95.1	68.3	49.3	39.5
	As ‘in-basin` consumption	13.4	25.6	64.8	52.8	32.9	27.0
	As ‘in-basin’ useful consumption	8.6	16.1	41.6	28.3	21.1	15.4
BaU-HD	As withdrawal for ‘in-basin’ use	23.1	41.4	107.9	76.3	63.0	39.5
	As ‘in-basin` consumption	15.5	25.9	74.2	57.7	42.1	27.0
	As ‘in-basin’ useful consumption	9.8	16.3	47.6	31.0	25.7	15.4
WM	As withdrawal for ‘in-basin’ use	21.3	40.5	106.0	79.3	61.3	38.7
	As ‘in-basin’ consumption	13.8	25.3	73.6	57.7	40.0	27.0
	As ‘in-basin’ useful consumption	10.9	19.7	46.0	39.7	31.5	21.1
WM-2	As withdrawal for ‘in-basin’ use	28.4	50.1	109.4	85.2	73.6	45.5
	As ‘in-basin` consumption	15.6	26.3	75.1	54.9	40.3	27.4
	As ‘in-basin’ useful consumption	11.5	19.3	48.1	35.3	29.2	20.0
EFR-L	As withdrawal for ‘in-basin’ use	21.3	39.2	105.3	75.1	54.2	35.6
	As ‘in-basin` consumption	13.8	24.6	73.1	54.8	34.9	25.1
	As ‘in-basin useful consumption	10.9	19.2	45.6	37.1	27.0	19.5
EFRL & H	As withdrawal for ‘in-basin’ use	21.3	37.0	94.2	58.3	62.3	27.7
	As ‘in-basin consumption	13.8	23.4	65.9	45.38	39.1	20.10
	As ‘in-basin’ useful consumption	10.9	18.2	41.0	29.56	30.3	15.17

Dependable Surpluses: The model yields monthly water balances for each year of simulation for each basin and under each scenario. This also includes the water available in each month, at the critical point near the end of the basin, over and above that required to meet the demands (including the curtailed demand in failure years) and the environmental flow requirements. From this monthly information, the annual surpluses have been computed and this information has been further abstracted as the 75 % dependable annual surpluses. These are presented in Table 9. Seventy-five percent dependable annual surplus flows at critical stations, over and above environmental thresholds is also depicted graphically in Figure 6.

Water Balances: As stated above, monthly water balances, year-wise, basin-wise and scenario-wise are available. As an illustration, useful abstraction, the annual water balances for the WM scenario for Narmada Basin for one year (1992) is shown in Table 10.

Table 9. Seventy-five percent dependable annual surplus flows at critical stations, over and above environmental thresholds (10^9 m^3).

Basin	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	16.62	14.40	16.03	14.53	15.09	11.83
Cauvery	0.12	0.12	0.12	0.12	0.12	0.12
Godavari	21.61	13.29	14.55	12.55	13.39	5.26
Krishna	0.12	0.12	0.18	0.12	0.12	0.12
Mahanadi	29.20	19.79	19.19	21.13	23.94	13.47
Narmada	0.12	0.12	0.12	0.12	0.12	0.12

Figure 6. Limits of use out of total endowment of 37 BCM, Brahmani-Baitarni Basin.

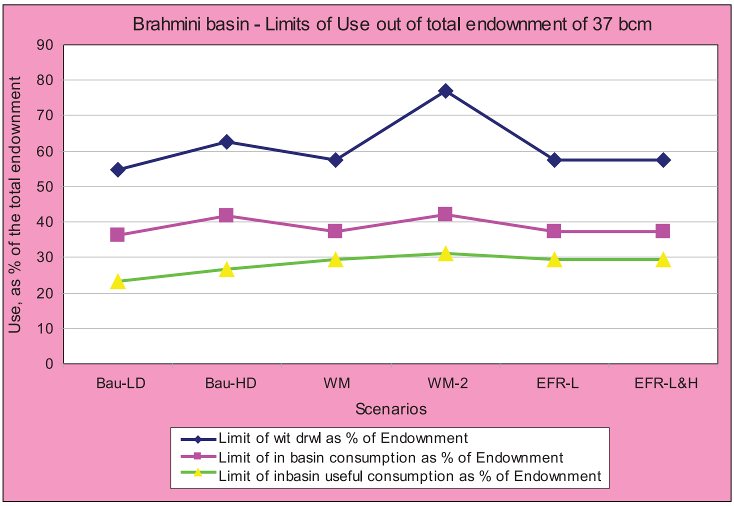


Table 10. Overall water balance for one year (year like1992) (WM scenario), for Narmada Basin (all fig. in $10^6 m^3$).

Basin	Natural flows	Imports	Total resource	Surface with-drawls	Return to surface	Surface storage filling	Reservoir evaporation	Exports	Subtotal, reductions in resource through surface water	Reduction in resource through GW	Total reduc tion in resource	Residual outflow
Narmada	34,059	0	34,059	18,143	3,668	-4,479	2,487	11,000	23,483	8,490	31,973	2,086

The anthropogenic changes in the groundwater regime are also revealed in the body of the results. Under the anthropogenic changes there would be both additional anthropogenic recharge and additional anthropogenic withdrawals (by pumping) for use. This has quality and quantity implications. On the quantitative side, if the anthropogenic recharge is less than anthropogenic withdrawals, the average GW regime will change by making corresponding reductions, as compared to the natural state, in its outflows. If the GW outflows decrease a new dynamic steady state will be achieved through a reduction in GW level and storage, to strike a new balance through a reduction in the base flow. This will have both social and environmental implications, since some deep-rooted trees may be drawing water from the GW reservoir. To understand this in comparative terms, we compared the anthropogenic changes in the groundwater inflows and withdrawals for each scenario. Any plan of water use in any scenario that required large reductions in GW base flow, as compared with the natural situation, were not accepted. The comparison in regard to the Krishna Basin for a year like 1992 under the 2025 situation is shown in Table 11.

Table 11. Krishna Basin—anthropogenic changes in groundwater regime (all fig. in $10^6 m^3$) for 2025 development condition and 1992 natural hydrologic situation.

Scenario	BaU-LD	BaU_HD	HD-WM	HD-WM2	EFR-L	EFR-L&H
Annual anthropogenic GW withdrawal	26,037	26,037	23,561	31,855	20,386	19,333
Annual return to GW, including anthropogenic returns	16,799	19,158	22,509	27,920	21,952	16,006
Consequent reductions in base flow, as compared with 'natural'	9,238	6,879	1,052	3,939	-1,206	3,327

Note: The scenarios were so adjusted that these regime changes do not appear unacceptably large.

Target Irrigation Areas and Failures in Irrigation

As stated, the target irrigation areas for different scenarios, for each of the basin along with the distribution of these areas in the seven crop seasons, were decided by trial and error. This was done so as to obtain the following:

- acceptable residual flows on the downstream;
- acceptable number of failure years in which the targets are required to be reduced (around 25 % of the total years in the simulation);
- acceptable level of the storage at the end of the simulation; and
- acceptable anthropogenic changes in the groundwater table.

The summarized results for all basins and scenarios are given in Table 12.

The net irrigation possible in each basin under each scenario, as compared with physical limit on the net irrigation possible is depicted in the Table 13. This clearly brings out that for the Krishna Basin, its endowment in terms of land does not get utilized in any scenario because of the limited water endowment; whereas in Cauvery, Narmada, as also in the Godavari , much of the land endowment can be effectively used in the WM scenario. In all these four basins, the irrigation area has to be reduced significantly if environmental constraints are added to the WM Scenario. As a contrast, the Mahanadi Basin, where again, improved water management

Table 12. Target irrigation areas (1,000 hectares) by scenarios basin-wise.

	BaU-LD	BaU-HD	HD-WM	HD-WM2	WM-EFRL	EFR-L &H
Brahmani-Baitarni						
Total GIA	2,500	2,600	2,800	2,800	2,800	2,800
Total NIA	1,708	1,708	1,708	1,708	1,708	1,708
Cauvery						
Total GIA	3,835	3,874	5,110	4,810	4,940	4,650
Total NIA	3,365	3,398	3,750	3,750	3,620	3,450
Godavari						
Total GIA	10,440	12,340	13,920	12,528	13,800	12,392
Total NIA	8,700	10,525	11,745	10,397	11,595	10,614
Krishna						
Total GIA	5,750	6,364	8,381	7,375	8,291	6,034
Total NIA	4,760	5,250	6,920	6,080	6,350	4,980
Mahanadi						
Total GIA	5,780	6,360	9,180	8,180	8,216	8,216
Total NIA	3,818	4,064	5,789	5,050	5,789	5,789
Narmada						
Total GIA	4,000	4,000	5,200	5,100	4,755	3,850
Total NIA	2,951	2,951	3,830	3,830	4,024	3,442

Table 13. Limits of possible irrigation areas, in % of max possible NIA.

Basin	Presen-t	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	73	98	98	98	98	98	98
Cauvery	60	89	90	99	99	96	91
Godavari	43	70	85	94	84	93	85
Krishna	24	34	38	50	44	46	36
Mahanadi	42	65	69	98	86	98	98
Narmada	48	72	72	94	94	99	84

is necessary for the full use of the land endowment, no irrigation is required to be given up while imposing environment-related restrictions. The Brahmani Baitarni Basin is so richly endowed with water, that all land can be irrigated in all scenarios.

The incidence of failures could be computed in two ways. There are seven possible crop seasons, which we have considered. These are the three 4-monthly crop seasons, three possible 8- monthly crop seasons and the perennial crops. These seven crop seasons irrigated from two sources (SW and GW) in the 15 years of simulation represent 210 source season years.

The percentage of source season years involving failures among these is one measure. Without considering the seasons, and the source, the number of years would be 15 and the percentage of failure years in another measure. The computations have been done using both measures. As an illustration, the failures for Krishna are depicted in Table 14.

Table 14. Failures in all scenarios, Krishna Basin.

Summary of failures	BaU-LD	HD	HD-WM	HD-WM2	WM-EFRL	EFR-L &H
KRISHNA						
Percentage by source-season-years	6.19	7.14	8.10	8.57	6.19	6.67
Percentage by years	20	20	20	20	20	33.33

Basin-wise Results

As an illustration, some details of the results for Brahmani-Baitarni Basin are presented below. The Brahmani-Baitarni Basin has an estimated average natural flow of 37x 10^9 m^3. No imports and exports are contemplated in the present study and thus the total endowment is 36.9x 10^9 m^3. The Figure 6 shows that in terms of useful in-basin consumption, only 30 % of this water can be used in WM, WM-2, EFR-L and EFR-L&H and the consumption would be lesser in other scenarios. In terms of total in-basin consumption only about 40 % of the endowment would get consumed as evapotranspiration. In terms of withdrawal, the WM-2 scenario would be able to withdraw around 77 % of endowment, whereas the scenarios with better water management (WM, EFR-L, and EFR_L&H) would require a withdrawal of 57 % of the withdrawal.

The basin has a current net sown area 1.94 Mha, which we assume would continue upto 2025, with some 0.2 Mha as the unavoidable rain-fed area in plateau lands without enough groundwater, the maximum NIA would be around 1.74 Mha against the present NIA of 1.27 Mha. The full available area has been proposed to be irrigated in all future scenarios. Thus land and not water is the constraint for in-basin use in the Brahmani-Baitarni Basin. In terms of GIA, we have assumed that for the NIA of 1.7 Mha the GIA cannot exceed 2.8 Mha. With the assumed cropping pattern having perennial and two seasonal crops hardly any irrigable land would be lying unoccupied in the *kharif* season. The occupancies as resulting from assumed cropping pattern are shown in Figure 7.

As mentioned, the land and not water is the restriction in the in-basin use in Brahmani-Baitarni Basin. Table 15 shows the 75 % dependable surplus flows at critical station over the environmental flow for Brahmani-Baitarni Basin and different scenarios.

Thus for Brahmani-Baitarni Basin a dependable surplus of $16.68*10^9$ m^3 is available in the BaU (low development) scenario which decreases to $14.46 * 10^9$ in the BaU (high development) scenario. With more efficient water use through water management activities, the surplus can be increased to $16.09*10^9$ in WM scenario. However, when the low-flow EFR constraint is used, the surplus reduces to $15.15*10^9$ m^3 when both low-flow and high-flow constraints for environmental flow are imposed, the surplus reduces to $11.89 * 10^9 m^3$.

Figure 7. Brahmani-Batarni: WM scenario—occupancies under assumed cropping pattern.

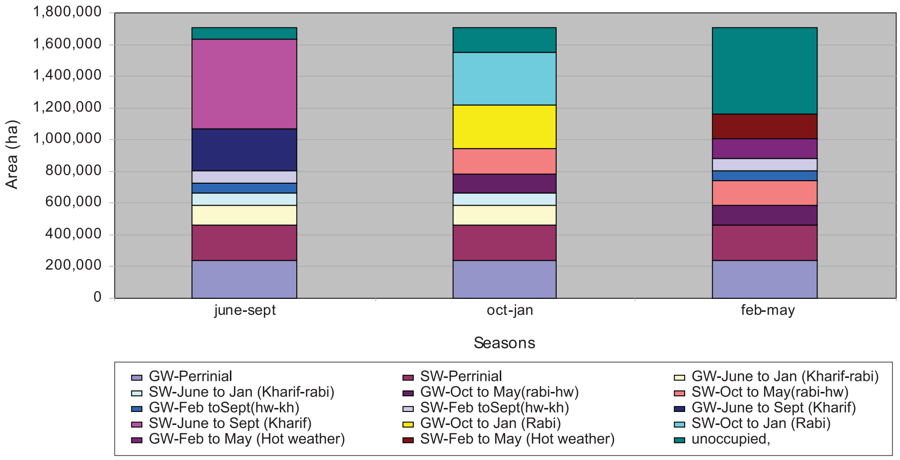


Table 15. Seventy-five percent dependable surplus flows at critical station, over and above environmental thresholds.

Basin	BaU-LD	BaU-HD	WM	WM-2	EFR-LOW	EFR-L & H
Brahmani-Baitarni	16.68	14.46	16.09	14.60	15.15	11.89

Concluding Remarks

The main purpose of the study was to demonstrate the process of scenario building, and of the assessment of the basin water situation for the scenarios. The process involved a conceptualization of the scenario, and its refinement to obtain the desired reliability in meeting the water use and environmental targets, through trial and error.

Another purpose of the study was to build alternate developmental scenarios for the six peninsular basins. This was to be done both for the purpose of a demonstration purpose, and also for generating good information about the capability of the basins in supporting in-basin development, with and without additional large interbasin transfers.

An important purpose of the study was to investigate the utilizable resources of the basins without considering additional interbasin transfers. As stated in the paper, the authors feel that the 'utilizable resource' is a complex concept, which depends, among other considerations, also on how the utilization is done and, therefore, the concept of the variable, 'limits of utilization' needs to be preferred. These limits would depend both on the basin characteristics and on the developmental strategies. The limits on both the withdrawals and the consumption under each scenario have been presented in Tables 8, 12 and 13 and they show a large variation among the scenarios.

The studies clearly bring out that the water resources of the Brahmani-Baitarni, Mahanadi and Godavari basins, and that their water endowments are far more than what could be used in the basins even after considering the current and committed imports and exports, and possible future uses. Thus, these basins are candidates for supporting additional water transfers without reducing the in-basin use possibility.

In regard to the Narmada Basin, where large exports from the basin are already envisaged, the studies bring out that the full potential of in-basin development for irrigation cannot be achieved, particularly in the low-development and high-development scenarios of the ‘business-as-usual’ strategy. Almost the full development can be achieved in the scenarios involving improved water management (The WM, WM-2, EFR-L and EFR-L&H scenarios). Thus for the full in-basin development of Narmada, either improved water management practices need to be installed or some reduction in the already committed export needs to be considered.

The studies establish that for Krishna and Cauvery basins, the water endowments are not enough to reach the full in-basin development potential. The Krishna Basin, even under these circumstances, is currently an exporting basin. Considerable water is being exported to Pennar and other east flowing rivers. The current study has not covered these basins which import the Krishna waters and it is likely that both equity and marginal productivity considerations would justify such exports even from a basin, which is not rich in water endowments. The basin also exports water for hydroelectric purposes, to the already water-rich west-flowing rivers. Thus there is a case for either reducing the exports from or increasing the exports to the Krishna Basin. Similarly, there is a strong case in considering new imports to the Cauvery Basin.

The study brings out the impracticability of continuation of the ‘business as usual’ approach in the water-stressed basins, by bringing out the effects on the limits of utilization, as also the effects on groundwater regime and on residual flows.

The study has also shown that the scope for in-basin development only through construction of additional storage-based projects is rather limited in the Krishna, Cauvery and the Narmada basins. This is because on one hand the basins of Krishna and Cauvery already have built a large number of storage facilities so that the marginal utility of additional storage facilities would be comparatively less (in both cases the terminal reservoirs hardly ever spill and the basins are effectively closed), and on the other hand because there are hardly any significant storage facilities remaining to be built. For the Narmada also, large storage projects are under construction and these would be completed in the next few years; after which there is hardly any scope for in-basin storage facilities.

The current studies have been done under some data limitations and assumptions. While the studies may have to be repeated when better data and information becomes available, the authors believe that the overall conclusions are unlikely to change substantially.

The limits of development of all the six basins under the six scenarios have been established, and the surplus water available in the three well endowed basins of Brahmani-Baitarni, Mahanadi and Godavari have been computed. However, large-scale plans for further water transfers, somewhat on the lines of the current plans of the National Water Development Agency (NWDA) have not been investigated in the current studies. While the dependable surpluses can be exploited, however, these are available mostly in the monsoons. Their use may require the construction of additional storage facilities in the surplus basin or the transfer of floodwater into additional storage facilities elsewhere, as well as changes in the current reservoir operation and in-basin uses. These possibilities may constrain the use of all the surplus water. This aspect requires a separate study as a continuation of the present one.

A separate scenario HD-WM2 which focuses only on drainage improvement and reuse has been created, and one of the main purposes of water development is to increase the useful consumption of water within the hydrologic, engineering, land-availability-related, and environmental-related constraints. The comparison of the WM and WM2 scenarios is presented in Table 8.

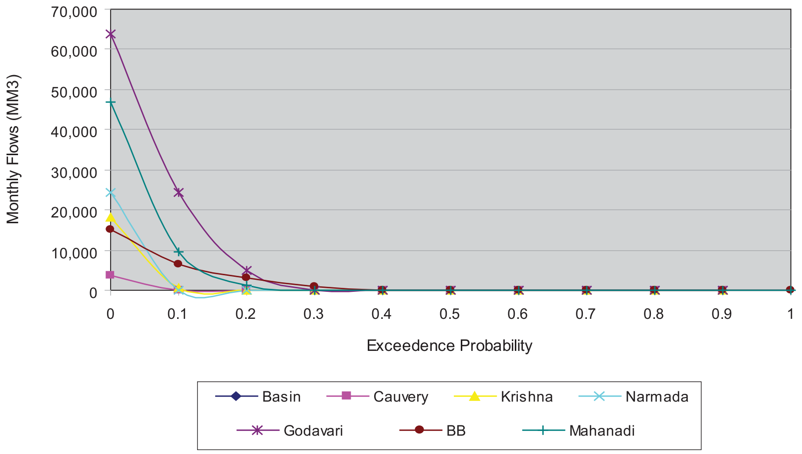
The study shows that it is difficult to maintain the environmental flows and, in particular, the environmental flows for maintaining the flood regime, in the relatively stressed basins, without reducing other uses. For example, in the Krishna Basin a useful in-basin consumption through irrigation $35.3*10^9m^3$ is possible in the WM scenario and this gets reduced to $29.6*10^9m^3$ for the EFR-L&H scenario. The desirability of providing a large environmental flow requirement is to be considered against these consequent reductions in in-basin consumptions. The societal preferences in this regard need to be established through studies, debates and trade- offs in a multi-stakeholder and multidisciplinary environment.

The study allows a comparative analysis of the scenarios, by developmental and environmental objectives, for each of the studied basin. While the choice of appropriate scenarios is considered outside the scope of the present study, such an analysis will allow the decision maker to reach the decision, or at least to shortlist a few scenarios for further socioeconomic analysis. To illustrate this point, a comparative analysis for the Krishna Basin has been included in the detailed report (www.nrlp.iwmi.org) and is abstracted below.

- The BaU LD scenario for Krishna involves an unacceptable groundwater regime and indicates that a large fall in groundwater table would take place under this scenario.
- The BaU HD scenario for Krishna indicates that with increased storage, and increased surface irrigation, without corresponding increase in groundwater irrigation, a slightly better groundwater regime can be expected.
- The HD-WM scenario for Krishna indicates, that with improvements in drainage as also water distribution efficiency, a still better groundwater regime can be obtained along with the largest possible irrigated area among the scenario. However, low flows would be too low.
- The HD-WM2 scenario for Krishna indicates, that if only the drainage improvements is done without canal efficiency improvements the irrigated area would have to be some what lower than the HDWM scenario.
- The EFR-L scenario for Krishna indicates, that as compared to WM scenario, significant irrigation has to be given up for maintaining the low flows. In the process, the groundwater regime, in this scenario is the best among all. However, the incidence of spills is the least among all scenarios and this may have adverse effects on the ecology and morphology.
- The EFR L & H scenario for Krishna indicates, that both in terms of consumption and possible irrigation, this scenario, indicates a situation in between the BaU LD and BaU HD scenarios. Thus, all the effort in improved water management through the drainage improvements and distribution efficiency improvements, and a part of the efforts in creating additional storage, go only towards the maintenance of environmental flows in both the low flows and high flows. The groundwater regime, is not as good as in the WM scenarios. However, spills or controlled flushing floods would be available each year.

Annexure-1.

Residual flows at critical point above threshold for WM scenario-flow duration curve.



Annexure 2.

Terminology

In India, due to marked seasonality in rainfall, seasonal crops are very common. These are roughly 4-month crops; the wet season (south-west monsoon, June-Sept, *kharif*), the autumn season (Oct-Jan, *rabi*) and the dry-hot season (Feb-May, hot weather) are common. Nomenclatures and the calendar can vary. Also, apart from perennial, some two season crops also prevail.

The 'gross cropped area (GCA)' indicates the total cropped area (rain-fed and irrigated) and includes the area which is cropped more than once. If and only the irrigated area is so counted the nomenclature used is 'gross irrigated area (GIA)'.

The 'net sown area (NSA)'is the geographical area which is under crop, at least for some time, during the year. If only irrigated area is counted the geographical coverage is known as 'net irrigated area (NIA)'. (Note that these intensity-related parameters do not really depict the intensity of occupation. For example, if the whole area of 100 ha were fully occupied in an year under sugarcane, the GCA would have been only 100 ha and the cropping intensity would have been 1.0, but if the land was fully occupied in June-September, occupied to 50 % in October - January, and occupied to 10 % in February-May, under seasonal crops, the GCA would have been higher at 160 ha.

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