CPWF Project Report

Tackling Water & Food Crisis in South Asia: Insights from the Indo-Gangetic Basin

Project Number 60

Bharat R. Sharma, Upali A. Amarasinghe, G. Ambili (Editors)

International Water Management Institute
Colombo, Sri Lanka

for submission to the

CGIAR Challenge Program on
WATER & FOOD

March 2010

Acknowledgements

The International Water Management Institute and the CPWF Project on “Basin Focal Project for the Indus-Gangetic Basin” are greatly pleased to acknowledge very active support and cooperation provided by the following institutions and individuals to make the project a great success and create the desired impact:

1. Dr. Simon Cook, Basin Focal Projects Coordinator, CIAT/ CPWF, Colombo
2. Dr. Larry Harrington, Director-Science and Dr. Ngyun Sophie Khoa, CPWF, Colombo
3. Dr. David Molden , DDG (Research), IWMI, Colombo and Dr. Madar Samad, Regional Director, IWMI, South Asia, Hyderabad, India
4. Dr. Vladimir Smakhtin, Theme Leader-I, IWMI, Colombo, Sri Lanka
5. Dr. Peter G McCornick, Director-Water Policy, and Ms. Heather Hosterman, Duke University, Durham, USA
6. Dr. Alok K Sikka, Technical Expert (Watershed Development), National Rainfed Area Authority (NRAA), New Delhi, India
7. Dr. Devaraj de Condappa, SEI Associate, Stockholm Environment Institute, Puducherry, India
8. Dr. Alan Brooks/ Dr. William Collis/ Dr. Mohammad Giasuddin Khan/Mr.Mohammad Golam Mustafa/Ms. Susana Hervas Avila, WorldFish Center, Dhaka, Bangladesh.
9. Dr. Anil K Singh, DDG (NRM), Indian Council of Agricultural Research, Krishi Bhawan, New Delhi, India
10. Dr. M A Khan, Director, ICAR-RCER, Patna, India
11. Prof. Rajendra Singh, Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur, India
12. Dr. Dipankar Chakraborty and Dr. Bhaskar Das, School of Environmental Studies, Jadavpur University, Kolkata, India.
13. Prof. A K Gosain, Indian Institute of Technology, New Delhi, India
14. Dr. Mohammed Allauddin, University of Queensland, Australia
15. Dr. Wais Kabir, Executive Chair, Bangladesh Agricultural Research Council, Dhaka, Bangladesh
16. Mr. Shree Krishna Adhikari, Nepal Agricultural Research Institute, Kathmandu, Nepal
17. Dr. Mushtaq Gill, ex-Director General, Directorate of On-Farm Water Management, Lahore
18. International Fund for Agricultural Development (IFAD)
19. European Union

Program Preface:

The Challenge Program on Water and Food (CPWF) contributes to efforts of the international community to ensure global diversions of water to agriculture are maintained at the level of the year 2000. It is a multi-institutional research initiative that aims to increase the resilience of social and ecological systems through better water management for food production. Through its broad partnerships, it conducts research that leads to impact on the poor and to policy change.

The CPWF conducts action-oriented research in nine river basins in Africa, Asia and Latin America, focusing on crop water productivity, fisheries and aquatic ecosystems, community arrangements for sharing water, integrated river basin management, and institutions and policies for successful implementation of developments in the water-food-environment nexus.

Project Preface:

CPWF-IWMI "Basin Focal Project for the Indus-Gangetic Basin" is an initiative by the CPWF, to identify steps to be taken towards integrated management of the IGB's water and land resources to improve productivity and ensure future sustainability of all production and ecosystems in the basin. The project was developed with the objective of conducting basin-wide analysis of the conditions, constraints and opportunities for improving agricultural water productivity and alleviating poverty through high potential interventions. This objective was accomplished through rigorous analysis and mapping of water availability and access, poverty, and productivity of water and identifying potential interventions that contribute to improved water productivity and poverty alleviation in the Indo-Gangetic basin.

CPWF Project Report Series:

Each report in the CPWF Project Report series is reviewed by an independent research supervisor and the CPWF Secretariat, under the oversight of the Associate Director. The views expressed in these reports are those of the author(s) and do not necessarily reflect the official views of the CGIAR Challenge Program on Water and Food. Reports may be copied freely and cited with due acknowledgment. Before taking any action based on the information in this publication, readers are advised to seek expert professional, scientific and technical advice.

Citation:

Sharma, Bharat R; Amarasinghe, U A; Ambili, G. (Eds.) 2010. **Tackling Water and Food Crisis in South Asia: Insights from the Indo-Gangetic Basin**. Synthesis Report of the Basin Focal Project for the Indo-Gangetic Basin, Challenge Program on Water and Food and International Water Management Institute, Colombo, Sri Lanka. x+120 pages

Contributing Authors

Chapter No.	Title	Authors
	Research Highlights/ Executive Summary	*Bharat R Sharma*
1.	**Basin Focal Project for the Indo-Gangetic Basin: An Introduction**	*Bharat R Sharma*
2.	**The Indo-Gangetic Basin: A Regional Perspective**	*Bharat R Sharma , G. Ambili*
3.	**Water Availability and its Access in the Indo-Gangetic Basin**	*Luna Bharati, Devaraj de Condappa, Bharat R Sharma*
4.	**Water Productivity in the Indo-Gangetic Basin**	*Cai Xueliang, Bharat R. Sharma, S Hervas, M.G. Khan, M.G. Mustafa, M. Alauddin*
5.	**Agrarian Change and Water Institutions in the Indo-Gangetic Basin**	*Tushaar Shah, Aditi Mukherji, Sanjiv de Silva, Dhruba Pant, R.P.S. Malik, S. Hervas, M.G. Khan*
6.	**Interventions for Improvement of Water Productivity in IGB region**	*Bharat R Sharma, Asad Qureshi, Dhruba Pant, G. Ambili, M. G. Mustafa, S. Hervas, M.G. Khan, M.Rahman*
7.	**Water-Land-Poverty Nexus in the Indo-Gangetic Basin**	*Upali A. Amarasinghe, Stefanos Xenarios, G. Ambili, R. Srinivasulu, Atul K. Singh, Dhruba Pant, Asad Qureshi, Madar Samad*
8.	**Knowledge Management and Impact of the BFP Indo- Ganges**	*Mir Abdul Matin, Bharat R Sharma*

CONTENTS

Topic **Page**

RESEARCH HIGHLIGHTS 1
EXECUTIVE SUMMARY 3

Chapter-I: Introduction

1. Basin Focal Project for Indo-Gangetic Basin: An Introduction

1.1. The Basin Focal Project and the Indo-Gangetic Basin 5
1.2. The Work Packages 5
1.3. The Scheme of Analysis 6
1.4. Structure of the Report 6
1.5. Project Partners 7

Chapter-II: Project Objectives

2. The Indo-Gangetic Basin: A Regional Perspective

2.1. The Indo-Gangetic Basin 8
2.2. Key Features of the Basin 9
2.3. Climate and Hydrology of IGB 10
2.4. Water Resources of the Basin 10
2.5. Water Related Hazards 12
2.6. Water Governance 13
2.7. Challenges in the Basin 14

3. Water Availability and Access in the Indo-Gangetic Basin

3.1. Introduction 16
3.2. Basin Level Water Availability and Demand 16
3.3. Water Balance Analysis at Sub-basin Level 24
3.4. Threats to Future Availability of Water Resources 28

4. Water Productivity in the Indo-Gangetic Basin

4.1. Water Productivity and its Estimation at the Basin Scale 31
4.2. Water Productivity of Rice-Wheat Cropping System in the Indo-Gangetic Basin 32
4.3. Annual Economic Water Productivity of Rice-Wheat Cropping System 38
4.4. Factors Affecting Variation in Crop Water Productivity 39
4.5. Fisheries Water Productivity in the Eastern Gangetic Basin 42
4.6. Sustainable Rural Development through Improved Water Productivity 50
4.7. Conclusion 50

5. Agrarian Change and Water Institutions in the Indo-Gangetic Basin

5.1. Role of Agrarian and Water Institutions in the Indo-Gangetic Basin 52
5.2. Is Irrigation Water Really Free in the IGB? 52
5.3. Energy-Irrigation Nexus in IGB 55
5.4. Irrigation and Agrarian Tenancy in the IGB: A Rapid Appraisal in 45 Villages across Nepal 60

5.5. Institutional Dynamics in the Pond Fishery in the Eastern IGB 63
5.6. Laws and Water Resources Governance in the IGB 64

6. Interventions for Improvement of Water Productivity in IGB Region

6.1. Development of Intervention Matrices and Prioritization of Crop-production Interventions 68
6.2. Identification of Potential Interventions using Analytical Hierarchy Process 70
6.3. Potential Interventions for Selected Crops 72
6.4. High Potential Interventions for Improving Water Productivity in IG Basin 74
6.5. Potential Interventions for Improving Fisheries Productivity in Eastern IG Basin 78

7. Water-Land-Poverty Nexus in the Indo-Gangetic Basin

7.1. Poverty in the Indo-Gangetic Basin 79
7.2. Spatial and Temporal variation of Poverty 80
7.3. Water-Land-Poverty Nexus 83
7.4. Water-Land-Poverty Nexus Analysis at the Household and District level 88
7.5. Water-Land-Poverty Nexus: Lessons from Case Studies in India, Pakistan and Nepal 92
7.6. Conclusions 95

Chapter-III: Outcomes and Impacts

8. Knowledge Management and Impact of the BFP Indo-Ganges

8.1. Introduction 97
8.2. End Users and Beneficiaries 97
8.3. Impact Pathways 97
8.4. Data Management and Database Development 102
8.5. Research Products 103
8.6. Dissemination and Impact Creation 104
8.7. Strategy for the Future 105
8.8. International Public Goods 106
8.9. Partnership Achievements 107
8.10. Recommendations 108
8.11. Publications 109
Bibliography 113
Project Participants 116
Appendix-Abstracts of some key publications 117

LIST OF TABLES

Table No.	Title	Page
2.1	Socio-economic indicators of the Indo-Gangetic basin countries.	9
2.2	Average annual discharge of the Indus tributaries.	11
3.1	Water demands in the Indus, down to Kotri; and Ganges basin, down to Farakka.	16
3.2	Distribution of water demands in the Indian part of the Ganges basin, down to Farakka.	18
3.3	Distribution of water uses in the Indus basin, down to Kotri.	18
3.4	Criteria for estimating in each sub-basin the setting quality of WEAP-Indus and WEAP-Ganges.	20
3.5	Simulation ability of the current WEAP-Indus and WEAP-Ganges.	20
3.6	WEAP-simulated average change in annual stream flow in some locations of the Ganges basin when temperature increased gradually over 20 years as compared to the reference scenario (1982-2002).	28
3.7	WEAP-simulated average change in annual stream flow in some locations of the Indus basin when temperature increased gradually over 20 years as compared to the reference scenario (1982-2002).	29
4.1	Marginal physical product (MPP) of water in rice production in Bangladesh during selected sub-periods.	36
4.2	Compound growth rates in marginal productivity of water in rice production for selected sub-periods.	36
4.3	'Hot spots and 'bright spots' in average rice water productivity growth by season.	37
4.4	River water fish productivity by weight and value of three river catchments in the G-M sub-basin.	45
4.5	Water productivity by weight and value of shrimp culture in selected ponds in three districts in G-M sub-basin, Bangladesh.	47
4.6	Water productivity by weight and value of some selected rice-fish and IAA systems in G-M sub-basin, Bangladesh.	47
4.7	Main constraints for improved fish culture in the study districts in GM basin, Bangladesh	47
5.1	Farm gate price relative to diesel price in IGB countries.	54
5.2	Impact of the *Jyotirgram* Scheme on different stakeholder groups.	59
5.3	Efficiency of different institutions on the basis of fishers' and fish-farmers' perception at three study villages.	64
6.1	Intervention categories and interventions for improvement of water productivity in IGB region.	69
6.2	Estimated water productivity values under selected studies for different crops in IG basin.	71
6.3	Sample of expert opinion for improving of water productivity of trice crop in IGB.	72
6.4	Ranked interventions for improving water productivity of rice in IGB.	73
6.5	Three most important interventions for improving water productivity of selected crops of IG basin.	73
6.6	Water productivity improvement in rice-wheat systems of IGB by different RCTs.	75
6.7	Aggregate reduction in crop water requirements possible with drip irrigation in India.	75
6.8	Improvement in delivery efficiency (%) as a means of watercourse improvement (USAID project).	76
7.1	Poverty gap and square poverty gap in India, Pakistan, Bangladesh and Nepal.	81

7.2	Poverty indicators in the Indian part of the Indo-Gangetic basin.	83
7.3	Parameter estimates, standard errors and odds ratio of the logit regression Model.	88-89
8.1	Knowledge management activities under the BFP-IGB project.	97
8.2	Impact on various beneficiaries of the project.	98
8.3	Summary description of the BFP-IGB project's main impact pathways.	100
8.4	Different type of data requirement for analysis under the Work-packages of the project.	103

LIST OF FIGURES

Figure No.	Title	Page
2.1	The Indo-Gangetic basin map.	8
2.2	Flow diagram of of the Ganges river and its major tributaries.	11
3.1	Digital Elevation Model (DEM) of the IGB region.	17
3.2	Available observed stream flows in the IGB.	19
3.3	Quality of the setting of WEAP-Indus and WEAP-Ganges.	20
3.4	Average contribution of glaciers to annual and seasonal stream flows in the Ganges basin down to Farakka, as simulated for the period 1982-2002.	22
3.5	Average contribution of glaciers to annual and seasonal stream flows in the Indus basin down to Kotri, as simulated for the period 1982-2002.	23
3.6	Simulated impact of canal withdrawals on the average monthly stream flow in some locations of the Ganges basin, period 1982-2002.	24
3.7	Sub-basin map of Gorai river catchment, Bangladesh.	24
3.8	Water balance at each sub-basin of Gorai River Catchment during 1965-1975.	25
3.9	Water balance at each sub-basin of Gorai River Catchment during 1990-1997.	25
3.10	Effect of land use changes on average monthly inflow to the Gorai catchment, Bangladesh.	26
3.11(a), (b)	(a) Upper Ganga sub-basin till Kanpur, India; (b) The main rivers and canal system in the Upper Ganges sub-basin.	26
3.12	Average annual water balances which include rainfall, evapo-transpiration and run-off from sub-basins within the Upper Ganga catchment.	27
3.13	The distribution of sub-catchments in Upper Ganga sub-basin	27
3.14	Variation of actual evapo-transpiration in the sub-catchments of Upper Ganga sub-basin.	27
3.15	Water balance calculations for sub-basins of the Koshi catchment.	28
3.16	Simulated impact of on average monthly stream flows in some locations of the Ganges basin of a gradual increase in temperature over 20 years, as compared to the reference scenario (1982-2002).	29
3.17	Simulated impact of on average monthly stream flows in some locations of the Indus basin of a gradual increase in temperature over 20 years, as compared to the reference scenario (1982-2002).	30
4.1	Percentage of crop cultivated areas for the year 2005-2006 in the IG basin.	32
4.2	Administrative boundary, ET, yield and water productivity of rice in the IGB for year 2005.	33
4.3	The histogram distribution of rice and non-rice cropland ET in IGB for the period of 10 June- 15 October 2005.	33
4.4	Yield, ET, and water productivity of wheat in the IGB for the year 2005-2006.	35
4.5	'Hot spots' and 'bright spots' of growth in *kharif, rabi* and annual rice crop average water productivity.	38
4.6	Hypothetical scenario portraying current and desirable environmental capital intensity in agricultural production in the context of Bangladesh.	38
4.7	Water productivity of rice-wheat rotation system in IGB and the contribution of rice to rice-wheat system water productivity.	39
4.8	Water productivity of all *kharif* crops in Indian part of the Indo-Gangetic basin.	39
4.9	Comparison of factors affecting water productivity in the Indus-Gangetic basin.	40
4.10(a) & (b)	Relationships between (a) water productivity and (b) yield and evapo-transpiration of rice.	42
4.11	The histogram distribution of WP values for rice and wheat.	42
4.12	*Beel* fisheries (2002-2007) productivity for 14 districts of Bangladesh.	44
4.13	Spatial variation of *beel* fisheries productivity in Gorai-Madhumati sub-basin.	44
4.14	Spatial variation of *baor* fisheries productivity in Gorai- Madhumati sub-basin.	44
4.15	Temporal variation of *baor* productivity in the GM basin.	45

4.16	Variation in river fish production in the G-M sub-basin, Bangladesh.	45
4.17(a), (b), (c)	Fish productivity elevation models (PEM) of (a) culturable ponds, (b) derelict ponds, and (c) culture ponds in the GM sub-basin, Bangladesh.	46
4.18	Impact of water resources development projects on open water fish productivity in G-M sub-basin, Bangladesh.	48
5.1	Irrigation sub-economies of South Asia.	53
5.2(a) & (b)	(a) Electricity networks before JGS, (b) Electricity networks after JGS.	58
5.3	Growth of policy and legal instruments in IGB countries.	64
5.4	Frequency of policy making and legislation in the frameworks in the IGB.	64
5.5	Orientation of water sector legal instruments between water resource development, management and governance in the IGB.	65
5.6 (a) & (b)	(a) Laws enacted in India by decade , (b) Water-related laws enacted in India by decade.	65
5.7	Emergence of groundwater policy and legislation in IG basin countries.	65
5.8	Dominance of groundwater laws in India (1990-2009).	66
6.1(a), (b), (c)	Crop-wise mean water productivity based on (a) total water use, (b) irrigation water use, and (c) actual evapo-transpiration.	71
6.2	Savings in water use by delayed transplanting over total rice area in Punjab for two rice varieties (PR113 and PR 115).	77
7.1	Human Development Index (HDI) and Human Poverty Index (HPI) rankings of few selected Asian countries.	80
7.2	Rural, urban and total head count ratio of India, Pakistan, Bangladesh and Nepal.	81
7.3	Povery maps across National Sample Survey regions in India; districts in Pakistan and *zilas* in Bangladesh.	82
7.4	Spatial variation of HCR in Indus-Gangetic basin.	83
7.5	Framework for understanding water-land-poverty nexus.	84
7.6	Changes in (a) per capita GDP and (b) per capita agriculture GDP with total head count ratio in Indian states.	85
7.7	Head count ratio in rural areas versus net irrigated and groundwater-irrigated area.	86
7.8	Rural head count ratio across land holding classes in Indian states.	87
7.9	HCR and per cent population with drinking water supply in the premises and using toilet facilities.	88
7.10	Distribution of households and rural headcount ratio according to extent of household’s primary employment and education of the head of the household.	90
7.11	Distribution of households and rural headcount ratio according to (a) extent of irrigation of the cultivated area, and (b) cultivated area of marginal and small holder irrigators.	91
7.12	Distribution of households and rural headcount ratio according in different land holding sizes in NSSO55th and 61st round.	92
8.1	Framework for impact pathways for the CPWF Basin Focal Projects.	98
8.2	Impact pathway networks for IGB countries.	99
8.3	Ground-truthing to support satellite image analysis for the IG basin.	102
8.4	Snapshot of website developed for Basin Focal Project- Indus Gangetic basin.	104

RESEARCH HIGHLIGHTS

The Basin Focal Project for the Indus-Gangetic basin (IGB) addressed the challenge of alleviating poverty in the Indus-Gangetic Basin through targeted interventions, which improved water productivity of the basin. The research in its course of two years, conducted an assessment of the water resources, the effectiveness at which the available water is used, institutional set-up that determine the access to water and the complex inter-linkages between water and poverty. The findings of the research are summarized below:

i. Groundwater is the dominant water source and under threat in the IG basin. Rapid agriculture expansion and subsequent utilization of available water resources of the basin has placed the basin at risk with water scarcity issues on one hand, and flooding problems on the other, the scales of which are further exacerbated by impacts of climate change. Glacier contribution to the river flows is significant in the basin, especially in the Indus basin. Improved land land use changes can significantly increase flows, providing more freshwater flow into the Sundarban mangrove forests.

ii. Public irrigation systems grossly under-price irrigation; but these are getting marginalized. despite massive government and donor investments. In the IGB, major challenge is to find ways of bringing down agricultural water use cost below the 'upper threshold' beyond which abundantly available water becomes too expensive for the poor.

iii. Though surplus food produced in the basin is the major source of regional food security, water productivity of both rice and wheat is generally low, implying great scope for improvement. General decline in water productivity is observed from Northwest to Southeast. In contrast to the bright spots of well performing areas, for example, Indian Punjab and Haryana, large areas come with extremely poor performance (eastertn Uttar Pradesh, Bihar and Bangladesh). The variability in water productivity shows no direct relationship with climatic conditions, implying the significance of irrigation infrastructure and associated crop and water management.

iv. Adopting Resource Conservation Technologies (RCTs) allow farmers to increase area, productivity and intensity of cropping. Delaying the transplanting of paddy to periods of low evapotranspiration saves precious groundwater and the energy; however the practice needs to consider the entire rice-wheat cropping system. Integrated aquaculture-agriculture and multiple water use systems have great potential in IGB, especially the eastern region.

v. High population growth is a significant driver of depleting and degrading natural resources. Head Count Ratio (HCR) has improved significantly in the recent years; yet, income of a large part of the rural poor population is well below the poverty line. Increasing access to land and water and improving productivity of irrigation can contribute to poverty alleviation among the small landholders, enhancing access to education and opportunities in non-farm employment are major pathways of reducing poverty among the landless.

EXECUTIVE SUMMARY

Indo-Gangetic basin, covering an area of 220 M ha and inhabiting about 1 billion people, is one of the most populous in the world and given the diversity of agro-climatic, social and economic conditions in the four riparian countries – India, Pakistan, Nepal and Bangladesh, it is clearly one of the most complex river basin systems in the world. Agriculture and water use patterns changed from largely rainfed to intensive irrigation through large canal systems and mighty dams (Mangla, Tarbela, Bhakra) including the world's largest contiguous irrigation system (Indus Basin Irrigation System). The basin is currently witnessing an unstoppable boom in groundwater pumping in its north-western parts . At the same time a large region in the eastern part of the basin (eastern India, Nepal and Bangladesh in Ganga basin) is unable to make good use of the available resource due to economic scarcity and policy inadequacy. Potential impacts of climate change on the Himalayan ecosystem and the changes in severity and frequency of floods shall further heighten the management challenges. Under such a challenging context, the Basin Focal Project for the Indo-Gangetic Basin (BFP-IGB) was launched in April 2008 with the objective of conducting basin-wide analysis of the conditions, constraints and opportunities for improving agricultural water productivity and alleviating poverty through high potential interventions. The stated objectives were achieved through six well-designed Work Packages (WP) of the Project: poverty and water-poverty analysis, water resources availability, assessment of water productivity, water institutions and policy analysis, intervention analysis; and knowledge management and impact analysis.

The project adopted a three-tier level of analysis (Basin- sub-basin- household) for better understanding of the basin's resources, productivity, people and the policies. For comprehensive understanding of the resources and productivity a basin-wide analysis covering the entire basin was attempted through the use of remote sensing/ GIS, climate and other publically (and internally) available large datasets. Further to study the impact of climate change and estimate the water balance components and other related studies, the national and regional level datasets (India, Pakistan, Nepal, Bangladesh) and sub-basin analysis for the four selected sub-basins (Rechna-Doab in Indus (Pakistan), Upper Ganga sub-basin (India), Koshi sub-basin in Ganga (Nepal/ China), and downstream Gorai sub-basin of Ganga (Bangladesh) was carried out. Since poverty, livelihoods and interventions is both a national and household phenomenon, well structured primary surveys were conducted to ascertain the responses of more than 2, 500 households, experts and peers in the villages and institutions spread throughout the basin. The project was implemented in collaboration with selected advanced research institutes and national partner organisations.

Major findings of the CGIAR Challenge Program on Water and Food supported 2-year Project **"Basin Focal Project for the Indo-Gangetic Basin"** have been synthesized in this Report. Some of the important recommendations which shall help in improving sustainability of the resources, enhance agricultural productivity and alleviate poverty are summarized below.

i. *Regional perspective*: Both from hydrological and socio-ecological perspective; the opportunities, constraints, strengths and weaknesses of the western IG basin are markedly different from eastern IG basin. Water and land resources are intensively utilised in the western region and are poorly or underutilised in the eastern region. The development frameworks and policies need to be regionally differentiated to ensure long-term sustainability in the north-western region and substantially improve the productivity and economic dynamism in the eastern region.

ii. *Use and abuse of water resources*: Most of the available water resources are utilised within the Indus basin leaving little scope for horizontal expansion. The strategic options are improving productivity levels of crops, move towards high value diversified and precision agriculture and release some water from irrigation sector to meet the growing demands of domestic, industrial and environmental flow requirements. Net discharge from the Ganges basin (37%) accounts for more water than any other use. Additionally, the basin also has a massive and presently unutilised static groundwater resource of about7,796 BCM. The Ganges basin countries may immediately initiate sound groundwater development and use policies which will help in improving productivity, reduce climatic vulnerability and also alleviate poverty.

iii. *Managing climate- change induced glacier melt flows*: Modelling estimates show that likely temperature increases (1°C to 3°C) will increase stream flows in the upper reaches of Ganga and substantially in the Indus. Using this extra water would require the ability to withdraw and use/ store (possibly through Managed Aquifer Recharge) during the high flows. Suitable resource development and use strategies need to be put in place to make good use of this short-to-medium term opportunity.

iv. *Improving agricultural productivity*: The average WP for the rice-wheat rotation system is low at 0.131 US $/ m3 whereas the 'bright spot' areas (about 5% of basin area) has high water productivity of 0.190 US$/m3. If the basin average value could be increased to the 'bright spot' level, the basin could theoretically save 31 % of agricultural water consumption with same quantity of production or increase 31% of production with same quantum of water input. This shows a great opportunity for improving productivity through a set of physical and policy interventions.

v. *Potential interventions for improving water productivity:* As access to the water resources is relatively poor in large parts of the basin, the critical crop water requirements are inadequately satisfied and crops experience different degrees of water stress. Knowledge on critical growth stages and improved management for specific crops in different regions should be made available to farmers so as to facilitate proper irrigation scheduling. Adoption of resource conservation technologies such as reduced/ zero tillage, laser land levelling, raised bed planting and direct seeding of rice need to be better promoted for consolidation of the scale benefits. Policy measures like regulatory delay in transplanting of paddy and breaking the water-energy nexus on the pattern of *Jyotirgram* Scheme shall improve groundwater governance. Multiple-Use Water Systems in the hilly areas of the basin and the eastern region shall significantly improve productivity and alleviate poverty of the small and marginal farmers.

vi. *Policy and institutional changes:* Energy infrastructure and policies in the eastern states need to be comprehensively and immediately improved so as to empower the millions of small and poor farmers operating at a very low level of agricultural productivity. The Groundwater Boards and Authorities in the basin countries need to be strengthened to move further from their present role of resource estimation to planning, development and management.

vii. *Managing the water-land-poverty nexus:* Reduction of pervasive rural poverty in the IG basin can be accelerated in a two-track approach: pro-poor agriculture growth interventions shall play a major role in reducing poverty in the agriculture operator households, and improving skills and enhancing opportunities for employment in the non-farm sector can reduce poverty among the agriculture labourers. Providing access to irrigation can help in substantial productivity improvement, diversification and thus reduction in poverty. Higher access to groundwater is associated with low poverty. Setting up of common/ co-operative tubewells managed by a small group of farmers may be a viable option for helping large number of marginal farmers with small holdings. Areas with small and fragmented holdings are hotbed of rural poverty in eastern IGB and need immediate policy changes towards consolidation. Access to infrastructure such as road, markets and electricity and quality inputs can also have a major influence in reducing poverty.

CHAPTER I

1. BASIN FOCAL PROJECT FOR THE INDO-GANGETIC BASIN: AN INTRODUCTION

Bharat R Sharma

1.1. The Basin Focal Project and the Indo-Gangetic Basin

Basin Focal Project for the Indo-Gangetic Basin (BFP-IGB) is an initiative by the Consultative Group on International Agriculture Research (CGIAR) sponsored Challenge Program on Water and Food (CPWF, http://www.waterandfood.org/). The international program on the Basin Focal Projects (BFPs) covering 10 major river basins in South America (Andes system, Sao Francisco), Africa (Volta, Niger, Limpopo, Nile) and Asia (Karkheh, **Indo-Gangetic**, Mekong and Yellow River) provide insights into the global condition of water, food and poverty disaggregated in sufficient detail to support interventions within river basins. Based on the best scientific and policy analysis the projects are designed to answer the pertinent questions on amount , spatial distribution and impacts of climate change on water resources in the basin; water use patterns by different sectors and stakeholders, assessment of the efficiency and productivity of water use and potential interventions for its improvement, evolution and effectiveness of water policies and water institutions and the factors affecting water-land-poverty nexus in the basin.

Indo-Gangetic basin, covering an area of 220 M ha and inhabiting about 1 billion people, is one of the most populous in the world and given the diversity of agro-climatic, social and economic conditions in the four riparian countries – India, Pakistan, Nepal and Bangladesh, it is clearly one of the most complex river basin systems in the world. Agriculture and water use in the basin has been as ancient as the history of mankind (> 5,000 years B.C.) and over the time has witnessed significant challenges to meet water and food needs of the vast and largely poor population. Agriculture and water use patterns changed from largely rainfed to river spate irrigation, small anicuts and barrages and shallow wells driven by animal power and to large canal systems and mighty dams (Mangla, Tarbela, Bhakra) including the world's largest contiguous irrigation system (Indus Basin Irrigation System). The basin is currently witnessing an unstoppable boom in groundwater pumping in its north-western parts (again creating a global hotspot in groundwater overexploitation as evident through GRACE; Rodell et al., 2009). At the same time a large region in the eastern part of the basin (eastern India, Nepal and Bangladesh in Ganga basin) is unable to make good use of the available resource due to economic scarcity and policy inadequacy. Potential impacts of climate change on the Himalayan ecosystem and the changes in severity and frequency of floods shall further heighten the management challenges. The basin also has to cope up with some of its unique problems like the arsenic contamination of groundwater in large areas, an endangered and large tidal dominated Gages delta and the transboundary nature of the river basin. Under such a challenging context, the Basin Focal Project for the Indo-Gangetic Basin (BFP-IGB) was launched in April 2008 with the objective of conducting basin-wide analysis of the conditions, constraints and opportunities for improving agricultural water productivity and alleviating poverty through high potential interventions. The stated objectives were achieved through six well-designed Work Packages (WP) of the Project.

1.2. The Work Packages

WP-1. Water Poverty Analysis: This component exhibits the dynamics of water, land and poverty nexus in the basin and how they are likely to evolve in the future. The analysis provided insights into the impacts of water and land property rights and use patterns on poverty and livelihoods in the vast region. Additionally, it attempted to test the hypothesis that development of intensive irrigation could contribute to land degradation and threaten the very benefits that irrigation has delivered to the rural people, in the first instance.

WP-2. Water Availability: This work-package aims at assessing the total resource (How much water is there, and where?) and water balance components in the basin. The analysis also attempted to assess the impact of climate change and upstream land use changes on water availability. Additionally, it looked into the question of how people access the available water resources.

WP-3. Water Productivity: Water productivity analysis first successfully attempted to develop a methodology for assessing basin-wide crop water productivity using publically available remote sensing/ GIS, national census and climate data products. Through an enriching collaboration with WorldFish Centre, the project was also able to develop and apply a methodological framework for estimating fish water productivity. This innovative research provided better understanding of basin performance on agricultural water utilization, map water productivity for major crops and fisheries, assess scope for improvement, and identify factors affecting water productivity in different parts of the vast Indo-Gangetic basin.

WP-4. Institutional Analysis: A set of studies under this package analyzed water institutions with a broad view encompassing water-related policies, laws and administrative structures as well as informal water institutions such as water user organizations, water markets and civil society organizations working in the water resources, energy and fisheries sector. The evolution of water governance laws in the four riparian countries (India, Pakistan, Nepal and Bangladesh) have been systematically analysed and organized for quick retrieval and reference.

WP-5.Intervention Analysis: This work-package aimed at identifying potential and productive physical and policy interventions capable of improving the water productivity and alleviating poverty in the Indo-Gangetic basin. A large matrix of interventions was developed to carry out the Analytical Hierarchy Process (AHP) analysis for identification of the most potential interventions for the important crops of the basin. Additional analysis was carried out to study the impacts of large-scale adoption of laser land levelling and resource conservation technologies, lining of canals and water courses, implementation of Punjab Sub-Soil Moisture Management Act, and improvement of different systems of culture and capture fisheries.

WP-6. Knowledge Management and Impact: The Knowledge Management and Impact package was designed to systematically acquire, process and disseminate data, information and new knowledge generated during the project. These efforts firstly supported other work packages in collecting and collating the data required for analysis and secondly to use various channels (website portals, blogs, publications, policy briefs, workshops and conferences etc.) to disseminate the new information/ databases and knowledge. Knowledge management aimed to share the information and knowledge products as international public goods and support decision making in the basin regarding productivity improvement and the investment decisions by donors and the governments.

1.3. The Scheme of Analysis

The project adopted a three-tier level of analysis (Basin- sub-basin- household) for better understanding of the basin- its potential, productivity, people and the policies. For comprehensive understanding of the resources and productivity a basin-wide analysis covering the entire basin was attempted which was made possible through the efficient use of remote sensing/ GIS, climate and other publically (and internally) available large datasets for the important parameters. Further to study the impact of climate change and estimate the water balance components and other related studies, the national and regional level datasets (India, Pakistan, Nepal, Bangladesh) and sub-basin analysis for the four selected sub-basins (Rechna-Doab in Indus (Pakistan), Upper Ganga sub-basin (India), Koshi sub-basin in Ganga (Nepal/ China), and downstream Gorai sub-basin of Ganga (Bangladesh) was carried out. Since poverty, livelihoods and interventions is both a national and household phenomenon, well structured primary surveys were conducted to ascertain the responses and advise of more than 2, 500 households, experts and peers in the villages and institutions spread throughout the basin.

1.4. Structure of the Report

This synthesis report entitled as ***"Tackling Water and Food Crisis in South Asia: Insights from the Indo-Gangetic Basin"*** is largely based on the research and synthesis reviews undertaken by the research team lead by IWMI. The report is organised under eight different chapters. The next chapter provides the unique regional perspective of the Indo-Gangetic basin highlighting its major challenges and the potential opportunities. Chapter 3 assesses the availability of surface and groundwater resources in the two basins, presents SWAT analysis for the selected sub-basins and develops the scenarios for the impact of climate change using glacier-melting sub-routine of Water Resources Estimation & Planning (WEAP) model. Chapter 4 briefly describes the new methodology of assessing and mapping basin level water productivity by integrating RS/GIS, national census and climate data products and presents the maps for rice and wheat; and fish water productivity and the factors affecting the variation in water productivity. The next chapter on water policy and institutions discusses results from a set of studies dealing with value of water, development and variation of water-energy nexus and the governing policies in the basin. A systematic study on the evolution of water governance laws and their effectiveness in the riparian countries of the basin is also presented. Chapter 6 presents the analysis on identification and prioritisation of the potential physical and policy interventions for improvement of water productivity and sustainability of the resources. The next chapter discusses the basic understanding and dynamics of water-land-poverty nexus at the basin, national, sub-national and household level. The analysis has generated poverty maps for the basin at different scales of analysis and attempted to better understand the relationships between rural poverty and agriculture and the access to water. Chapter 8 briefly discusses the knowledge management and impact networks for the project and the project plans for better dissemination of the information and new knowledge developed under the project so as to facilitate informed decision making about policy and investments in the basin. In the final chapter we summarise the important findings and recommendations for achieving the sustainability of the resource base, improving water (and land) productivity of the crops and fisheries and alleviating poverty of the vast rural populations whose livelihoods are dependent on these resources.

1.5. Project Partners

Large number of studies under the BFP-IGB were developed and implemented by a consortium of national and international researchers and a vast body of experts, peers, stakeholders, independent consultants, government departments and more than 2000 farm families in the basin. The core research team was lead by the International Water Management Institute (IWMI) with members from the following institutes/ organisations:

i. International Water Management Institute, Colombo and its offices at New Delhi (India), Lahore (Pakistan), and Kathmandu (Nepal)*: Lead institute*
ii. WorldFish Centre and its regional office at Dhaka (Bangladesh)
iii. Indian Council of Agricultural Research, New Delhi and its institutes
iv. Indian Institute of Technology, Kharagpur (West Bengal), India
v. Stockholm Environment Institute (SEI) - U.S. Centre
vi. Indian Natural Resource Economics and Management *(*INREM*)* Foundation**,** Anand, India
vii. Centre for Natural Resource Studies (CNRS), Dhaka, Bangladesh

The research team enjoyed the benefit of regular and expert advice from Dr. Vladimir Smakhtin (Theme Leader-I, IWMI), Dr. David Molden, DDG (Research), IWMI, Dr. Simon Cook (CPWF Basin Focal Projects' Coordinator) and Dr. Larry Harrington (CPWF Science Director).

CHAPTER II

This chapter presents all the relevant information and research results developed under the six well articulated work packages of the project. The chapter presents a detailed regional perspective of the Indo-Gangetic basin (Section 2), an assessment of the water resources in the basin and impact of climate change on the water resources (Section 3), development of a methodology an assessment of the basin level water productivity and factors affecting the variation (Section 4), agrarian change , water policy and institutions in the IG basin (Section 5) , potential interventions for improving the land and water productivity in the basin (Section 6),and finally an analysis of the water-land-poverty nexus in the basin countries and policies for its alleviation are presented (Section 7). These sections address the major objectives of the project and as the methodologies for each theme are quite varied, the same are presented at the appropriate place under each section.

2. THE INDO-GANGETIC BASIN: A REGIONAL PERSPECTIVE

Bharat R Sharma

2.1. The Indo-Gangetic basin

The Indo-Gangetic Basin (IGB, Figure 1), one of the world's most populous, has emerged during the past 40 years into an intricate mosaic of interactions between man and nature, poverty and prosperity and problems and possibilities. Rapid expansion in agricultural water use is a common theme across these interactions and access to water is central for the livelihoods of the rural poor. Given the diversity of agro-climatic, social and economic conditions in the four riparian countries—Pakistan, India, Nepal and Bangladesh—the IGB is clearly one of the most complex river basin systems in the world. The physical characteristics, socio-economic conditions and variable availability of water resources in the basin countries decide resource development and its use in the basin. Further, the transboundary nature of the basin adds more complexity to the water resource challenges and the potential solutions.

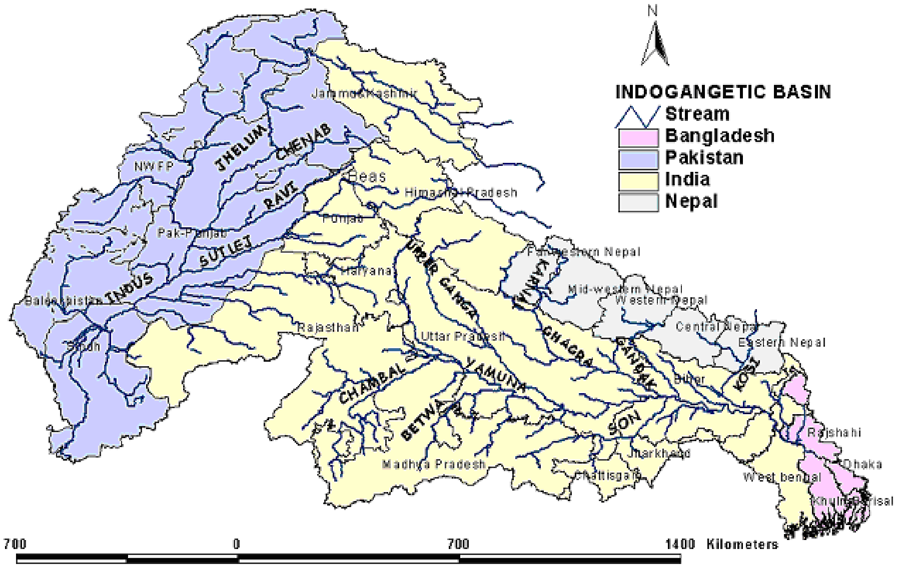


Figure 2.1. The Indo-Gangetic basin map (Source: http://dw.iwmi.org).

Indo-Gangetic basin is a composite basin drained by two mighty rivers; the Indus and the Ganges. Indus basin covers an area of about 110 million ha of which 63% is in Pakistan, 29% in India and 8% in China and Afghanistan (World Resources Institute, 2003; Jain et al*.,* 2009). The 3,199 km long Indus River originates in Mount Kailash in Tibet (China), and consists of Upper Indus and Lower Indus – the portions upstream and downstream, respectively of Guddu barrage in Pakistan. The river has two main tributaries; Panjnad on left bank formed by five rivers; the Jhelum, the Chenab, the Ravi, the Beas and the Sutlej Rivers and the Kabul on the right bank. Indus river waters are shared between Pakistan and India in accordance with the Indus Water Treaty (1960). The Ganges River has its source at Gangotri glacier near Gomukh (Uttarakhand, India). The basin covers an area of about 108.9 million ha, of which 79.2% lies in India, 12.85% in Nepal, 4.28% in

Bangladesh and the rest in Tibet and China. The major tributary of Ganges is the Yamuna, which merges with Ganga at Allahabad, after which it flows eastward and is joined by various tributaries along its course such as the Ramganga, the Gomti, the Ghaghra, the Gandak, the Bagmati, the Kosi, the Sone and the Damodar.

Hydro-geologically, the Indus Basin is filled with thick alluvial sediments deposited by the Indus River and its five main tributaries forming a thick set (300-500 m) of unconfined and leaky aquifers. Aquifer system in Pakistan-Indus consists of deep, unconfined aquifer, the geology of which consists mainly of young quaternary sediments. In India, the Indo-Gangetic basin from north to south is divisible into Himalayan region, sub-Himalayan region, *Bhaba*r zone, *Terai* zone, Central Ganga Plains (CGP) and Marginal alluvial plains. Similarly in Nepal, geological conditions exist as high mountainous Himalayas, Siwaliks and *Tera*i plains. In Bangladesh part of IGB, main aquifer is either semi-confined or consists of stratified/interconnected, unconfined water bearing zones.

2.2. Key Features of the Basin

The upper reaches of Indo-Gangetic basin constitute high mountains, mainly the Karakoram and Himalayan mountain ranges, having many peaks with height more than 7000 masl. These mountain ranges largely influence the weather conditions of the region by intercepting cold winds from the north and trapping moisture from the oceanic winds in south. Indo-Gangetic plain (IGP) forms the intensively cultivated area, with fertile soils formed by alluvial deposits. Downstream of Farakka constitute the Ganga delta region, characterized by silt deposits.

Social and economic heterogeneity is an important characteristic of the basin. IGB is one of the most populous regions in the world; the population of IGB is 747 million as per 2001 census (presently about 1 billion people). Rural population in Bangladesh, India, Nepal and Pakistan is 79.9%, 74.5%, 86.0% and 68.0%, respectively of the total population. Poverty is still a rural phenomenon in IGB, more than half of the rural poor of South Asia live in the IGB, and which could be well over 220 million people. In 2000, about 30.5% population in IGB is below poverty line. However, poverty is substantially higher in rural areas where the population depends mainly on agriculture directly or indirectly as their means of livelihood. In India much of the rural poverty is concentrated in few eastern states that fall in the Ganga basin. The Indus and Ganges basins will have some of the highest growth of population in South Asia in the first half of this century. Even by 2050, more than 61% of the rural population and 56% of the urban population of India will live in IGB. Selected indicators demonstrating the socio-economic conditions of basin countries are presented in Table 2.1.

The basin has a net cropped area of 114 million ha. Cropping systems are characterized mainly by rice, wheat, cotton and sugarcane crops besides several other minor crops. Among the grains, IG basin produces a major part of wheat production (93%) and more than half (58%) of rice production in the basin countries. In the lower parts of the Ganges basin in India and Bangladesh inland fisheries also form a significant component of the agricultural production system.

Table 2.1. Socio-economic indicators of the Indo-Gangetic basin countries.

Parameters	Bangladesh	India	Nepal	Pakistan
Access to improved water resources,%	74	86	90	91
Access to improved sanitation, %	39	33	35	59
Per capita electricity consumption, kWh	145	594	91	493
Population below national poverty line,%	49.8	28.6	30.9	32.6
Agriculture, % of GDP	20.1	18.3	38.2	21.6
Per capita GDP (USD)	406	640	252	632
IRWR* (m^3/capita/yr)	688	1149	7539	325

**Internally Renewable Water Resources*

(Source: Babel, M S; Wahid, S.M. (2008). Freshwater under Threat: South Asia; UNEP/ Asian Institute of Technology, Bangkok)

The basin as a whole and Indian region in particular is witnessing a good expansion in economy and income levels, which shall have substantial implications for future water and food requirements (Amarasinghe et al., 2007). However, the Indian economy is witnessing a transformation from agriculture-based to an industrial-based one, but still has large agriculture-based regions such as eastern Uttar Pradesh and Bihar (World Development Report, 2008). Land use, cropping and water use patterns are changing, partly as responses to changing demographics and consumption patterns, and partly as responses to changing investment scenarios and economic growth. From the socio-ecological perspective, the opportunities, constraints, strengths and weaknesses of the western IGB are markedly different from eastern IGB. The West has already developed its known water resources, while the east is still using a small fraction. At the basin scale, the eastern region (especially Bihar and eastern Uttar Pradesh states in India and Bangladesh) having the highest population densities was bypassed during the Green Revolution era and is still weak in rural infrastructure, developed markets, institutions, energy and credit for agricultural operations, location specific technologies, storage based surface irrigation systems and well developed groundwater resources. As such, continued flood- proneness and water logging, geogenic arsenic and acute agrarian poverty and unemployment are the outstanding challenges in the east. The western region was the seat of Green Revolution, has high productivity and good irrigation (now dominated by groundwater) and rural infrastructure and markets. Overall economic dynamism too is more pronounced in the West than in the east. In the west, the overarching issue is sustainable resource management; in the East, it is centrally about livelihoods, poverty and food security.

2.3. Climate and Hydrology of IGB

Great seasonal and spatial variations exist in the climatic parameters and this affects the hydrologic behavior of the basin as well. Rainfall increases from west to east, varying from less than 100 mm in the arid zones of the west to about 1,500 to 2,200 mm in the Ganges delta region. The west and trans-Himalayan region receives less than 1,000 mm precipitation annually (Mirza, 1997). On the other hand, evapo-transpiration follows an opposite pattern, increasing in the westward direction. The basin covers some of the arid regions in South Asia such as the Thar Desert with an annual rainfall of around 100 mm or less. In Upper Indus Basin, major portion of precipitation occurs in winter and spring, from melting snow and glaciers. In the Indian part of Indus basin, mean rainfall in the monsoon season ranges from 450 mm to 1,020 mm. Central parts of Indus basin receive substantial amounts of rainfall in the winter, due to western disturbances passing over the Himalayas. Altitudinal influence of precipitation is also noticeable; northern valley floors are arid, with annual rainfalls of 100 to 200 mm, whereas the accumulated rainfall is about 2,000 mm at 5,500 m elevation (Archer and Fowler, 2004). About 30% of the Indus basin in Pakistan receives an average rainfall of less than 250 mm annually (Habib, 2004). Inter-annual variability of rainfall is more pronounced, more than 70% of the annual rainfall is received from the south-west monsoon. Mountainous catchments of Chisapani, Devghat, Kampughat and Everest are marked with high precipitation, which exceeds potential evaporation. Chambal, in the extreme west Ganges is the driest sub-basin, whereas Devghat in the Himalayan region with its high mean annual precipitation forms the wettest sub-basin. Ganges basin catchments at lower altitudes generally have an average annual rainfall of 790 mm to 1860 mm and an annual potential evapo-transpiration in the range of 1,440 to 1,770 mm (Eastham et al*.,* 2009). ET_0 is higher in the south-western IGB, especially in southern Punjab and Sindh province of Pakistan, in the range of 1,700-2,100 mm.

Mean and minimum summer temperatures show a cooling trend (1961-2000) in Upper Indus basin (UIB), whereas mean and maximum winter temperatures have a warming trend. In contrast to most areas in world, a large increasing trend in diurnal temperatures has also been recorded in UIB (Fowler and Archer, 2006; Bhutiyani et al.; 2009). This could be the reason for the glacier advances predicted in western Himalayas in response to global warming, as opposed to other mountainous climates. These trends also have significant impact on the basin runoff. Runoff depths for Indus and its tributaries varies from around 100 to 1,500 mm, minimum at the downstream end, just above the discharges to Arabian sea at Kotri, and the maximum recorded in Ravi river at Mukesar. Runoff patterns are influenced by topographic and geological characteristics of the basin as well as the abstractions at various locations.

2.4. Water Resources of the Basin

Drainage area of Indus basin contributes an annual flow ranging from 120 BCM to 230 BCM (41 years average, 1957-1997). The upper parts of the basin receive most of its stream flow from the melting Himalayan glaciers. Average annual discharge of Indus and its tributaries are as given in Table 2.2. Western rivers of Indus basin contribute an average annual inflow of about 174 BCM, whereas inflow from eastern rivers is only 10 BCM. Average annual outflow from the basin to the Arabian Sea is about 45 BCM. Average flow in Ganges (Figure 2.2) varies from around 5.9 BCM in Tons river to about 459 BCM in main Ganges at Farakka barrage. At the point of confluence of Ganga with Yamuna at Allahabad, mean annual flow is about 152 BCM, of which 61% is contributed by Yamuna. Northern tributaries, especially those in Nepal, contribute more to the annual flow of Ganges (Jain, 2008).

Table 2.2. Average annual discharge of the Indus tributaries.

River	Station	Catchment area km^2	Mean annual runoff volume km^3	Mean annual runoff depth mm	Mean annual streamflow m^3/s
Indus	Attock	265,122	79.85	301	2,532.1
Indus	Kotri	832,418	90.43	109	2,867.6
Jhelum river	Baramula br.	12,494	6.98	559	221.4
Jhelum river	Munshibag	4,324	4.07	942	129.1
Jhelum river	Chinari	13,598	10.28	756	326.1
Chenab river	Panjnad	280,238	63.20	226	2,004.2
Chenab river	Akhnoor	22,681	25.12	1,108	796.6
Ravi	Mukesar	5,700	8.39	1,472	266.1
Beas	Mandi plain	18,274	15.68	858	497.3

Source: Global Runoff Data Centre

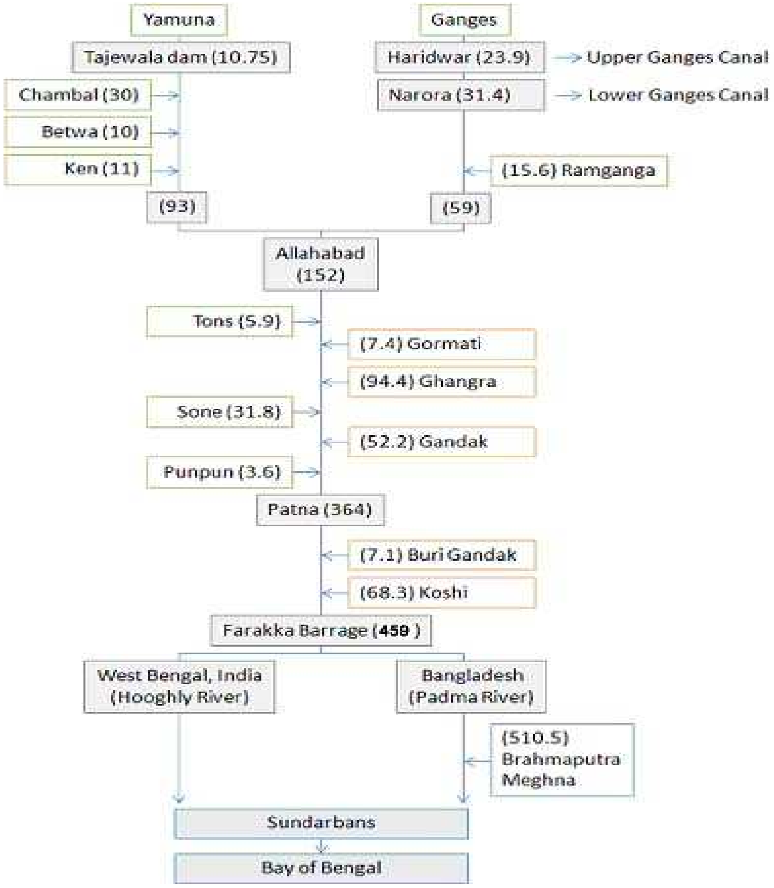


Figure 2.2. Flow diagram of the Ganges River and its major tributaries. [Tributaries originating in India are depicted in green boxes; tributaries originating in Nepal are depicted in orange boxes; and gauging stations are depicted in gray boxes. Numbers are average annual flows in billions of cubic meters (BCM)]. (Adapted from Jain et al., 2007 and Hosterman et al., 2009).

Groundwater availability is not uniform across IG Basin, certain areas in Indus part of the basin has a groundwater recharge of less than 0-2 mm/year while some areas in Nepal and Bangladesh have medium to high range of annual groundwater recharge. In Indian part, the states of Bihar, Madhya Pradesh, Uttar Pradesh and West Bengal account for almost two third of the net groundwater availability. In addition to the dynamic groundwater resource, the basin also has a total static groundwater resource of about 9,172 km^3, of which 85% is in the Ganges basin.

Water use in the basin is dominated by agriculture as about 91% of the annual water withdrawals in the basin are for agriculture, and 7.8% for domestic use. Indus basin houses the largest contiguous irrigation network in the world, the Indus Basin Irrigation System (IBIS), with a command of 17 Mha. The system diverts almost 75% of the annual river flows into the Indus basin. Other major irrigation projects in the basin include Bhakra-Nangal in Indian-Indus, and those in Ganges basin such as Sarda canal, Sone canal, Gandak scheme, Ganges-Kobadak (G K) project in Bangladesh, and Sunsari Morang Irrigation Project in Nepal. Groundwater resource utilization is high in western IGB, constituting the Indus basin. Groundwater extraction in regions such as Punjab (both Pakistan and India), Haryana and Delhi is almost unsustainable, with large areas classified as 'over-exploited'. Recent studies by NASA have classified this region as the world hot-spot in groundwater over- exploitation leading to fast decline of water tables (Rodell et. al., 2009). On the other hand, only 54% of the groundwater resources available are utilized in the Ganges basin. Demographic pressures and industrial development of IGB countries change the way the scarce water resources are utilized, studies indicating domestic and industrial water use expected to significantly increase in the near future (Amarasinghe et al., 2008).

2.5. Water Related Hazards

Hazardous events related to water such as floods, droughts, landslides etc. claim lives and cause serious damage to crops, livestock and infrastructure. The extent and severity of hazardous events are exacerbated by climate change. Indus basin is ranked among the top ten rivers in the world at risk, mainly from climate change. Melting Himalayan glaciers provide major source of water for irrigation. Predictions on alarming rate of retreat of glaciers, as for example the Gangotri glacier, signal the reduction of river flows and their impact on food production. Climate change predictions indicate 27% reduction in Indus basin inflows by 2050 (IPCC, 2001). Diminishing low-season flows put further pressure on groundwater resources, which is already over-exploited in the Indus basin region. Reductions in recharge caused by reduced surface runoff could also affect the groundwater resource base in the region. This is going to be critical for western IGB, particularly in India and Pakistan, where groundwater forms the major source of irrigation.

Floods are a common feature in the eastern IGB. Flooding in rivers is mainly caused by inadequate capacity within the banks of the rivers to contain higher flows, riverbanks erosion and silting of riverbeds, landslides leading to obstruction of flow and change in the river course, poor natural drainage due to flat floodplains and occurrence of coastal cyclones, and intense rainfall events. Ganga river basin and its tributaries like Yamuna, Sone, Ghagra, Gandak, Koshi and Mahananda witness annual floods. Among the South Asian Countries, India is more vulnerable to flood events, followed by Bangladesh (CRED International Disaster database). Riverine and inland flooding is also on the increase, especially in northern and eastern India and adjoining Nepal and Bangladesh. In Bangladesh, flooding occurs almost every year from the combined discharges of Ganges, Brahmaputra and Meghna rivers. Since 1954, Bangladesh has experienced 16 severe floods.

International or inter-state nature of these rivers specifically hinders the ability of governments to take up appropriate and timely measures for forecasting and moderating floods and further add to the complexity of flood problem in the riparian regions. Climate change is likely to further aggravate this problem as an annual mean increase in precipitation of 3 ±1% in 2020s, and 7 ±2% in the 2050s has been predicted for the region (Sharma and Sharma, 2008).

Droughts are also experienced in the western IGB. Crop and livestock damages during periods of drought deter the growth of agriculture dependent areas. Parts of Rajasthan, Haryana, Madhya Pradesh and Uttar Pradesh in India and Sindh province of Pakistan experience occasional droughts due to weak or delayed monsoons. Past three decades of data indicate that India is more vulnerable to drought compared to other IGB countries. About 51 million ha in the sub-continent is drought prone, which makes about 16% of its total geographic area. Pakistan experienced the most severe drought in 1998-2002, during which period surface water availability was reduced by over 30% (Muhammed et al., 2004). However, over the years the impact of droughts has diminished due to investments in water infrastructure and other adaptive and mitigation measures.

2.6. Water Governance

The transboundary nature of the basin necessitates strong governance system to be in place to assist on decision-making process of riparian countries on sharing of the two international rivers. For satisfactory utilization of Indus river waters, India and Pakistan concluded the *Indus Water Treaty* in 1960 with World Bank assistance, after much negotiation from both ends. By the treaty, the flow of eastern rivers (Ravi, Beas and Sutlej) and western rivers (Indus, Jhelum and Chenab) were made available for unrestricted use in India and Pakistan, respectively (World Bank, 1960). To replace the supply of water lost for irrigation earlier dependent on flows from eastern rivers, Pakistan was allowed to construct canals and storage dams on western rivers. The treaty also had provisions for Pakistan to build three dams, and other provisions on data exchange, future cooperation and establishment of a permanent Indus Commission for the conflict resolution and satisfactory implementation of the treaty.

Similar agreements, albeit less effective, exist for sharing of the Ganges waters as well; between India and Bangladesh and between India and Nepal. A thirty-year *Ganges Water Sharing Treaty* was signed between India and Bangladesh on December 1996 to share the dry season (January-May) flows in the Ganges River at Farakka (Mirza, 2002). Discharges during 1949-1988 were taken as the basis for deciding on allocation. According to the treaty, if the discharge at Farakka is less than or equal to 70,000 cusecs, India and Bangladesh get equal shares; for discharge between 70,000-75,000 cusecs, Bangladesh gets 35,000 cusecs and the rest is allocated to India; if discharge is equal to or more than 75,000 cusecs, India gets a fixed share of 40,000 cusecs and the rest is apportioned to Bangladesh. This sharing holds subject to the condition that each country receives guaranteed 35,000 cusecs in alternative three 10-day periods from March 1 to May 10 (Mirza et al., 2004). However, since the dry season flows are very small, the treaty discharges seldom happen. Similar agreements exist between India and Nepal in the form of Kosi treaty, Gandak treaty and Mahakali treaty. Kosi treaty was signed in 1954 (further amended in 1966), which envisaged the construction of a barrage at Bhimnagar for containing the meandering of Kosi river (World Bank, 2003). As per the Gandak treaty, concluded in 1959; a barrage, canal and other appurtenances were constructed for irrigation and hydropower development in Nepal and India. Mahakali treaty, for sharing the boundary river of Mahakali was signed in 1996 for the integrated development of the Mahakali barrage including Sarada barrage, Tanakpur barrage and Pancheswar Project. Forward looking treaties between India and Nepal and their implementation can potentially create win-win solutions for both the countries through development of hydropower and water resources and providing succour to the annually flood ravaged areas in Bihar (Kosi floods) and Bangladesh.

The significance of groundwater in agricultural economy of the riparian countries and the associated issues of groundwater depletion makes governance an essential component in the management of this valuable resource. Choice of suitable groundwater extraction mechanism is influenced by energy policies of the Government, thus exhibiting the nexus between the two. Punjab and Sindh in Pakistan started with public tubewells till 1990's, when electricity subsidy (60%) was introduced for private tubewell owners. Later when electricity prices started soaring up, diesel pumps became the favoured choice. With widespread governmental support as well as backing from donor agencies such as World Bank, India saw a surge in its energy use in agriculture, from 1950's to 1970. In early 70's, metering system was introduced, but incurred high transaction costs with increased number of tubewells. During 1970-80's, most of the Indian states shifted to flat-rate tariffs, based on horsepower of the pump (Shah et al., 2004). In eastern IGB, it was found to be unviable, but still could not opt for raised tariff, as a result of which rural power supply became more erratic , unreliable and almost dysfunctional. Dieselization was resorted to as a counter measure, in Indian states of Bihar, eastern UP and West Bengal and Nepal *terai* and Bangladesh. High cost of the diesel energy is one of the serious impediments for sub-optimal use of groundwater in the eastern region (Shah et al., 2009). Punjab, Haryana and Western UP in India enjoy real electricity subsidies, and electric pumps dominate in these regions.

Groundwater markets existing in some parts of IGB also ensure water access to those sections of farmers who lack the financial capacity to own a pump. Farmers pay either on an hourly rate (mostly for diesel pumps), based on area or a share of the crop (Mukherji and Shah, 2004), which is either outright payment, or in some cases as a tenancy arrangement. Flat rate of tariff for electric water extraction mechanisms causes farmers to charge on the basis of area per season. Shah et al (2006) has reported that IGB has highly evolved and active pump irrigation markets functioning in the region attributable to conjunctive use practiced in western IGB and to high natural recharge in eastern IGB. However, recently shrinkage is reported in groundwater markets due to the soaring diesel energy prices (Mukherji, 2007 and Shah et al., 2009).

2.7. Challenges in the Basin

A stark contrast is noticeable in water resources development and use in the western and eastern Indo-Gangetic basin. Western IGB is characterized by high levels of regional development, mainly attributed to infrastructure development in irrigation, which allowed maximum utilization of inputs and usher in the Green Revolution. On the other hand, eastern IGB still have considerable undeveloped resource base and lack of infrastructure and enabling environment which prevents this region from harnessing the true potential of the available resources. Major challenge faced by water managers working in this region is to find suitable instruments to bridge this gap in development, possible to an extent by increasing the productivity of water. There is also a need to address the problem of generating political environment and regional cooperation among the basin countries conducive to such developmental activities. Targeting investment in the least developed areas of eastern IGB (eastern UP, Bihar and West Bengal in India; Nepal *terai* and parts of Bangladesh) where rural poverty is also at its highest, could offer the rural poor a way out of poverty.

With rapid population growth, water allocation among competing sectors remains a big challenge to water managers. In addition to the rise in water demand, land-use changes contributed by population growth, particularly in the mega urban settlements of the basin, is also adding to the pressure on water resources. Future pressure on water resources by urban and industrial uses advocates the need for suitable strategies to combat reduced water availability for irrigation based on whether the water available would be enough to grow enough food to meet the requirements of the population. Over extraction of water for industrial and domestic purposes also leave less flow available for meeting environmental requirements. Intensive agriculture to feed the growing population steps up the use of chemical fertilizers, pesticides, herbicides etc. polluting much of the watercourses in the Ganges. This coupled with the alarming levels of industrial waste loads dumped to water bodies and sewage disposal in turn reduces the amount of utilizable flows. Challenges lie in checking sewage discharges from an ever-increasing population as well as effective implementation of policies to control industrial wastewater discharges. Government of India has recently established National Ganga River Basin Authority (2009) for initiating suitable steps for cleaning of the Ganga River.

Shrinking of Himalayan glaciers caused by global climate change decreases low season flows, increasing the vulnerability of already stressed water resources of IGB. IBIS, relying heavily on summer flows contributed by winter snow and ice in Himalayas and Karakoram, will be faced with new challenges with the change in snow and ice potential. Frequent droughts in dry western region and recurrent floods in eastern IGB, mostly Bihar in India and Bangladesh, cause huge economic losses, which gets much more severe with climate change. Farming systems and water use still has to find effective ways to adjust to such uncertainties in climate. Such adjustments has to be tapered to the regional needs as the level of adaptation needed for rural poor communities, especially in Bihar and Uttar Pradesh in India and Nepal *terai* and Bangladesh, to the impacts of climate change being different from those in urban settings. Advanced use of bio-technology aimed at developing and disseminating new varieties and the appropriate cultivation practices that can survive floods and drought spells are desperately needed to add resilience to the climate change adaptation measures.

The share of groundwater in water footprint of IGB is considerably large and is increasing at a rapid pace. Continuous and increased agricultural groundwater extraction contributed much to the regional development of Punjab (both Indian and Pakistan) and Haryana in western IGB, but these came at a cost of environmental degradation in the form of depleting water levels and quality degradation. Unsustainable levels of groundwater development in most areas of western IGB are favoured by inappropriate food procurement policy and energy subsidies that often fail to regulate over-exploitation of this valuable resource. Politics play a substantial role in this and reforms aimed at eliminating subsidies would be politically difficult. Although regulations exist on limiting groundwater extraction from dark and grey zones, governance is not efficient enough for their effective implementation. The real challenge lies in defining a groundwater policy framework, which allows for its future sustainability, but at the same time is acceptable to all the stakeholders. The framework should also be able to address the nexus existing between water, energy and food security in the basin. Policy-makers also need to understand and establish tradeoffs between sustainability and economic development. Some recent innovations like the enactment of Punjab

Sub-Soil Water Management Act (2009), wide scale adoption of laser land leveling and resource conservation technologies, aerobic rice and system of rice intensification and harnessing comparative advantage of boosting rice and fisheries production in the eastern region hold good promise in alleviating some of the basin challenges.

3. WATER AVAILABILITY AND ITS ACCESS IN THE INDO-GANGETIC BASIN

Luna Bharati, Devaraj deCondappa, Bharat R Sharma

3.1. Introduction

The Indo-Gangetic Basin (IGB) is a large basin of about 2.25 million km². Its main component is the Indus basin, of about 1.16 million km², which is shared by Afghanistan, India, Pakistan and Tibet (China) – Pakistan being the major country. Its other component is the Ganges basin, of about 1.09 million km², which is shared by Bangladesh, India, Nepal and Tibet (China) – India being the major country (Sharma et al., 2008). The topography of the IGB is much contrasted with upstream steep mountainous region of Himalayas and downstream plains in south of Pakistan, West Bengal and Bangladesh. Rainfall ranges from less than 250 mm/year in the West, in the Indus, to more than 3,500 mm/year in the East, in the Ganges, with an average rainfall of about 1,200 mm/year. The Himalayas are partly covered by glaciers that seasonally release water to the stream network of the IGB. The contribution from the glaciers to stream flows is supposed to be significant although no distributed quantification of this contribution is available in the literature. Moreover, there is uncertainty on the impact of climate change on glaciers and possible consequences on stream flows. The runoff ratio for the Ganga basin is 49%, i.e. mean annual runoff is 49% of the mean annual precipitation meaning that a significant amount of water is still available for use. In contrast the agriculture and other sectors in the Indus basin utilize most of its available water and the net runoff from the basin is only about 10% (Eastham et al., 2009).

3.2. Basin Level Water Availability and Demand

Assessment of surface and groundwater resources and the availability for different sectors is a great challenge in the Indus-Gangetic basin mainly due to transboundary nature and serious river-flow and related hydrologic parameters data access limitations and also for time and resource constraints of the project. The basin level water resources for the Indus basin and the Ganges basin has been attempted by Eastham et al. (2009) and is available at (http://cpwfbfp.pbworks.com/Water-use-in-River-Basins). Only a brief summary of these reports has been attempted here for the benefit of proper understanding. A digital elevation model of the IG basin is given at Fig. 3.1.In this chapter we present the results of WEAP modelling analysis and scenario building for the two basins. To reasonably address the data gaps and limitations and to address the objectives of the work-package, more detailed sub-basin analysis at representative locations was completed. These sub-basins include: Rechna- Doab in Indus basin (Pakistan), Upper-Ganga sub-basin (upstream Kanpur in India), Koshi sub-basin (Nepal and India) and Gorai-Madhumati sub-basin (in Bangladesh) for the Ganga basin

3.2.1. Estimate of water resources in the Indus and the Ganges Basin

The Indus basin has moderate annual average precipitation of about 750mm spatially averaged across the basin, and two metres or more in the northern Himalayan catchments. Net discharge from the basin is about 10 % of the total rainfall. Grassland is the most extensive land use, and hence the largest water user, followed by irrigation. About 8 % of irrigation water comes from groundwater. Irrigated agriculture, which covers 20% of the basin, has the second highest water use at 268,573 mcm. Rainfed agriculture, which covers 14% of the basin, has water use of 146,872 mcm, or 15% of the available water.

In the Ganges basin, water is plentiful during the monsoon period and frequent flooding occurs, particularly in downstream reaches and Bangladesh. In contrast, during the dry period between monsoons, areas become water stressed and flows may be inadequate to supply irrigation demand. All the sub-catchments of Ganga basin are subject to the influence of the summer monsoon, receiving the majority of their precipitation (67-92%) between June and September. Annual average runoff in the basin is 568,160 mcm, but shows large temporal variation ranging from 409,601 mcm in 1992 and 78,162 mcm in 1955. Runoff tends to decline after 1980, in parallel with a decreasing trend in rainfall from 1981 to 2000 (Bhutiyani et al., 2009). The mean annual input by precipitation to the Ganges basin totals about 1,170,000 mcm. Net runoff from the basin is about 429,000 mcm or about 37 % of the total precipitation input. Rainfed agriculture is the most extensive land use, covering 52 % of the basin. Its water use is correspondingly high, with a mean annual water use of about 371,000 mcm, or 30% of the water used (Eastham et al., 2009). Irrigated agriculture covers 25% of the basin, with 17% of the total area irrigated from surface water sources, and 8% from groundwater. The estimated mean annual water use by irrigated agriculture is about 286,000 mcm, or 23% of the total water use. Interestingly, net discharge from the basin accounts for more water than any other use, followed by rainfed agriculture. Irrigation is the third major water user, accounting for a little under a quarter of the total water use: one-third of the irrigation water comes from groundwater.

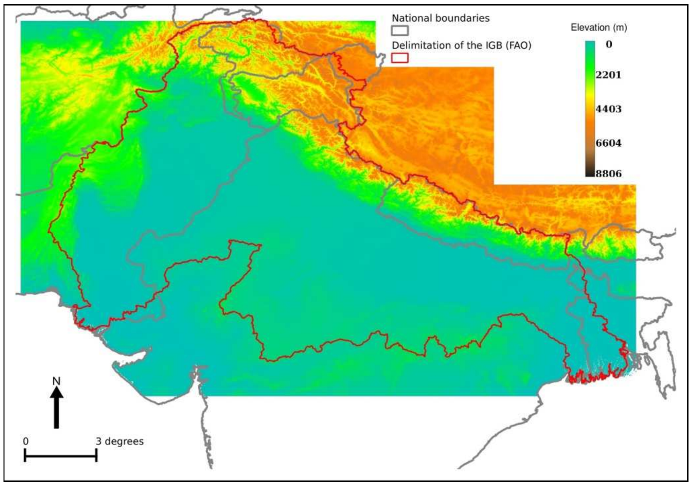


Figure 3.1. Digital Elevation Model (DEM) of the IGB region. DEM from Jarvis et al. (2008), delimitation of the IGB is from Integrated Data Information System (IDIS of IWMI/ CPWF).

3.2.1. Water allocation at the basin/sub-basin level

Amarasinghe et al. (2007) provides values for the three categories of water uses -irrigation, domestic and industries in Indian districts. Habib (2004) provides information on the same categories of water demands in the Pakistan part of the Indus basin. Table 3.1 reports the values of these demands in each basin. Water demands from irrigation, domestic and industrial sector for different sub-basins of the Indian Ganges basin is given in Table3.2. In the Indus basin, water demands are as given in Table 3.3. The water demands of the eastern part (Jhelum, Chenab, Ravi, Beas and Satluj rivers) are lumped into Pakistan and Indian demands in the sub-basin Panjnad.

Table 3.1. Water demands in the Indus, down to Kotri, and Ganges basins, down to Farakka.

Basin	Demands (km^3/year)*			
	Irrigation	Domestic	Industries	Total
Ganges	93.9 (82.08)*	10.7 (9.35)	9.8 (8.57)	114.4
Indus	168.7(95.50)	4.4(2.49))	3.4(2.01)	176.5

* Adapted from Amarasinghe et al. (2007), Habib (2004) and the Bhakra Beas Management Board (* Figures in parenthesis indicate percent values).

As evident from the data, water withdrawals for irrigation (total value and as percent fraction) are much higher in the Indus basin (95.5%) as compared to the Ganges basin (82.08%).

Table 3.2. Distribution of water demands in the Indian part of the Ganges basin, down to Farakka.

Sub-basin	Demands (MCM per year)[*] Irrigation	Domestic	Industries
Tehri Dam	**21**	**17**	**12**
Haridwar	56	55	37
Narora	2,477	140	103
Ramganga dam	19	21	14
Ramganga river outlet	5,938	391	292
Kanpur	9,853	753	573
Ganga at Allahabad	**1,848**	**141**	**108**
Tajewala	168	60	76
Delhi	8,107	1,066	2,059
Bisalpur dam	1,566	177	188
Gandhisagar dam	1,366	207	185
Rana Pratap Sagar dam	131	14	13
Chambal river outlet	8,128	664	670
Rajghat dam	996	124	110
Matatila dam	208	18	15
Betwa river outlet	1,937	151	131
Ken river outlet	1,484	150	134
Yamuna at Allahabad	**17,033**	**1,578**	**1,646**
Gomati river outlet	6,824	667	504
Asara Ghat	0	0	0
Ghaghara river outlet	8,156	1,061	772
Bansagar dam	462	130	115
Rihand dam	177	72	71
Sone river outlet	1,198	281	235
Gandak river outlet	1,002	202	109
Punpun river outlet	2,455	438	246
Budhi Gandak river outlet	1,612	476	238
Kosi river outlet	943	168	85
Farakka	**9,787**	**1,514**	**1,033**
Total	**93,952**	**10,736**	**9,773**

* *Water demands adapted from Amarasinghe et al. (2007)*

Table 3.3. Distribution of water uses in the Indus basin, down to Kotri.

Sub-basin	Water Demands (km^3/year)[#] Irrigation	Domestic	Industries
Panjnad (India)	34.7	1.0	1.4
Panjnad (Pakistan)	65.0	1.4	0.7
Sukkur	6.0	1.4	0.7
Kotri	63.0	0.7	0.7
Total	168.7	4.4	3.4

#Adapted from Habib (2004),

3.2.2. WEAP Modeling for Indus and Ganges basin

Water **E**valuation **A**nd **P**lanning (WEAP) modeling (http://www.weap21.org/index.asp?doc=14&cat=5 developed by Stockholm Environment Institute) was employed separately for the Indus and the Ganges basins mainly to:

i. Assess the water resources, in particular, contribution from glaciers
ii. Model its utilisation / planning ; and
iii. Provide insight into some possible future scenarios related to the impact of climate change on glacier and ice melt.

For this purpose, an application of the model *Water Evaluation And Planning* (WEAP) was set up which contained an experimental glaciers module that accounts for snow and glaciers processes in the IGB, i.e., seasonal mass variations and contribution to stream flows. The first step was to gather the input data, such as the digital elevation model, the land-use, climatic time-series, observed stream flows, glaciers coverage and water diversions / uses in the IGB. In the second step WEAP was calibrated and partly validated on the observed stream flows. As time-series of observed stream flows and glaciers area were scarcely available, the WEAP application developed in this work could not model precisely the processes and provided instead general trends. In a third step, WEAP model was applied to analyse the current context of the surface water resource in the IGB, in particular the contribution from melting of glaciers. The study also examined possible impacts of two 20-years scenarios:

(i) increase in temperature of +1, +2 or +3 °C,
(ii) decrease in initial glaciers area.

The prospect of this work is to pursue the development of the WEAP application in the Ganges basin by engaging collaboration with additional organisations operating in the Ganges. The input climate data were obtained from the *Climate Research Unit* (CRU). Glaciers coverage was taken from the IGB Tool Kit and the Global Land Ice Measurement from Space (GLIMS*)*. Salient features of large reservoirs and canals were also incorporated in WEAP. Additionally, Jain et al. (2007) provided general annual trends of the main river systems of the Ganges. The location of gathered time series is shown in Figure 3.2. It appears clearly that there was very few information in the Indian part of the Ganges basin. Except three stations in Upper Ganga (Haridwar, Narora and Kanpur), no time series were available and calibration relied on general trends from Jain et al. (2007). This is a serious drawback for a correct simulation of flows and water abstraction.

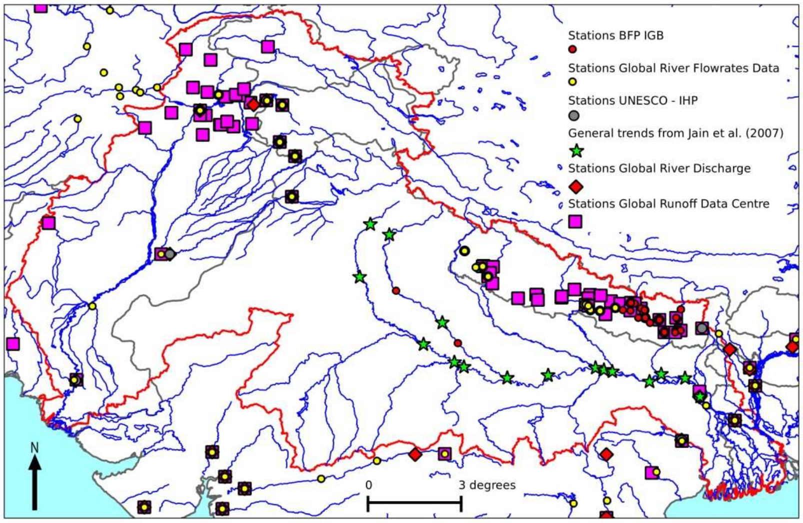


Figure 3.2. Available observed stream flows in the IGB. (Delimitation of the IGB boundary from IDIS, river network from FAO GeoNetwork. (*Note that the delimitation of the IGB and the river system shown here are from two different sources and sometimes inconsistent with each other*).

The Ganges and the Indus basins were sub-divided into sub-basins. The task of setting WEAP-Indus and WEAP-Ganges meant calibrating and possibly validating so as to reproduce the observed stream flows at the outlet of each sub-basin. Due to data and time constraints, the current versions of WEAP-Indus and WEAP-Ganges do not cover whole of the Indus and Ganges basins, but the part down to Kotri barrage (Indus, Pakistan) and Farakka barrage (Ganges, India), respectively. To evaluate the quality of the setting in each sub-basin, we defined criteria as presented in Table 3.4. It is noteworthy that these criteria may appear loose as they were chosen with respect to the scarcity of observed data in the Ganges.

Figure 3.3 shows the quality of WEAP-Indus and WEAP-Ganges in each sub-basin. Due to the scarcity of input data, the current WEAP-Indus and WEAP-Ganges are not reliable enough to consider results at the monthly or annual time scale. However, they can provide insight into average trends in the basins. We analysed their simulations referring to data in Table 3.5.

Table 3.4. Criteria for estimating in each sub-basin the setting quality of WEAP-Indus and WEAP-Ganges.

Category	Available observed data		Nash & Sutcliffe (1970) coefficient		$\frac{\sum \text{monthly flow simulated}}{\sum \text{monthly flow observed}}$	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
Excellent	Time series, ≥5 years	Times series available	≥ 0.9	≤0.8	Within [0.95,1.05]	Within [0.95,1.05]
Very good	Time series, ≥5 years	Times series available	Between [0.8,0.9]	Between [0.7,0.8]	Within [0.95,1.05]	Within [0.90,1.10]
Good	• Time series, <5 years • Or average trend + extra info	NA	Between [0.7,0.8]	-	Within [0.95,1.05]	-
Acceptable	Average trend	NA	-	-	Within [0.90,1.10]	-
Bad	Scarce info	NA	-	-	Not in [0.90,1.10]	-
Very bad	None	NA	-	-	Not in[0.90,1.10]	-

Table 3.5. Simulation ability of the current WEAP-Indus and WEAP-Ganges.

Quality of the setting in a given sub-basin	What can the WEAP applications simulate?
Very good to good	Monthly average trends
Acceptable	Annual average trends
Bad to very bad	Nothing!

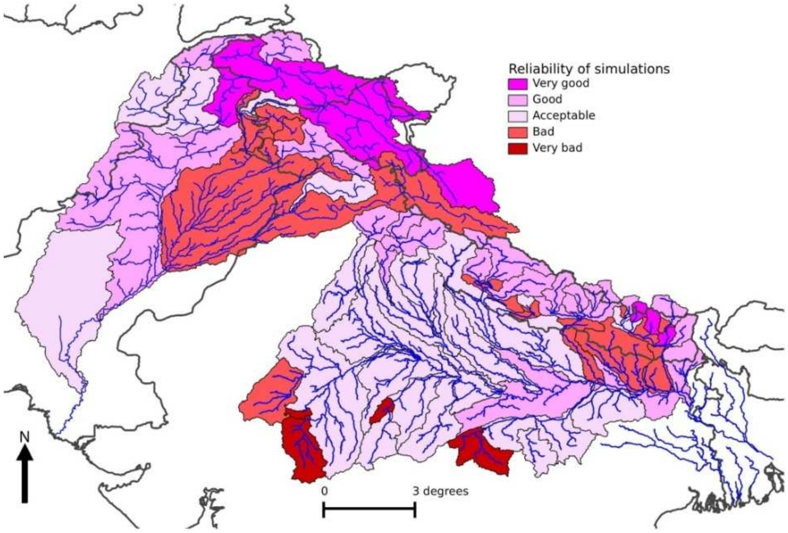


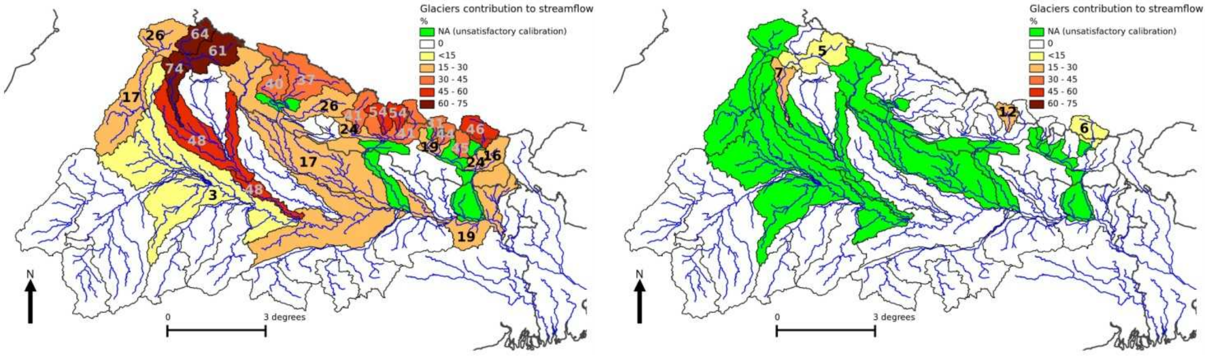
Figure 3.3. Quality of the setting of WEAP-Indus and WEAP-Ganges (based on the criteria defined in Table 3.4).

3.2.3. Contribution of snows and glaciers

Figure 3.4 shows part of the annual stream flows in the Ganges that comes from melting of glaciers. This contribution is important (60 to 75%) in Upper Ganges and in the Nepali sub-basins of the Ghaghara, Gandak and Kosi rivers (40 to 55%). This share, however, reduces significantly further downstream, falling to 19% at Farakka as glaciers' flows are diluted by stream flows from rainfall / runoff. Glaciers contribution is critical in the Indus basin as it equals 91% at Danyour Bridge, 64% at Tarbela dam and 90% at Kotri barrage (90%) (Figure 3.5).
The seasonal contribution of run-off is much contrasted in the Ganges basin .The flows from glaciers occur predominantly in the months of June to September, being almost nil in other months. The glaciers contribution is slightly more dispersed in the Indus basin (Figure 3.5) as the glaciers contribution is almost all the year around, although it is the highest between June to September.
Another interesting result is that glaciers are buffers against inter-annual variability of rainfall.

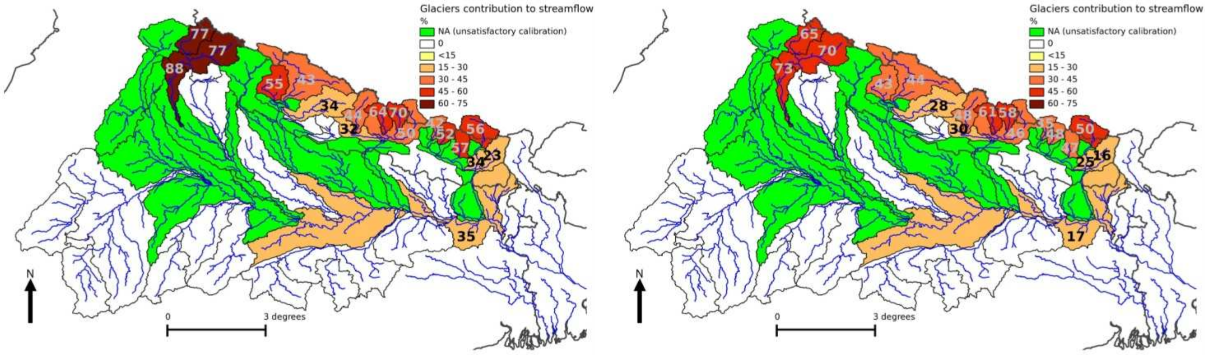
3.2.4. Effect of water development infrastructures: dams, reservoirs, water utilities

Impact of some canals on the stream flow is visible in Figure 3.6. At Haridwar (Upper Ganga canal) and Narora (Lower Ganga canal), the annual stream flow is reduced by about 25% and 15% after the withdrawal by the canals. Impact is mainly on low flows, during the months November to April. This is even more at Tajewala, along the Yamuna, since the annual stream flow is reduced by about 65% after withdrawals from the western and eastern Yamuna canals, leaving virtually no flows during the low flow season. WEAP-Indus is not precise enough to view the monthly impact but observed stream flows at Kotri in the 1970's show that flows during the low flow season was almost already reduced to 0.



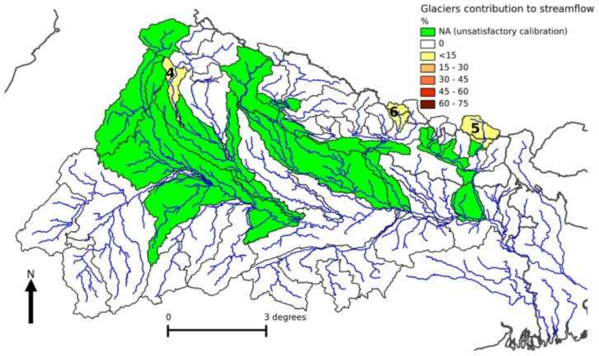
Annual

February to April



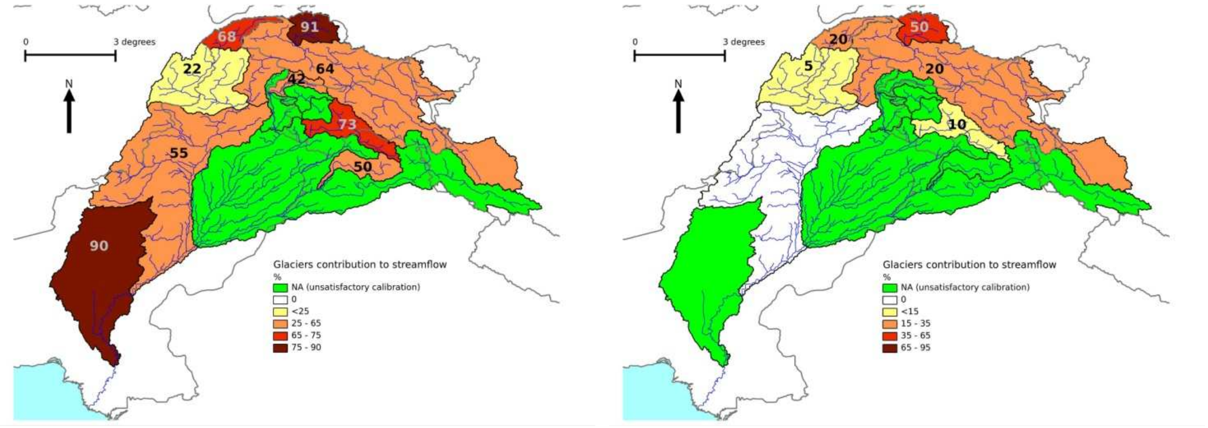
May to July

August to October



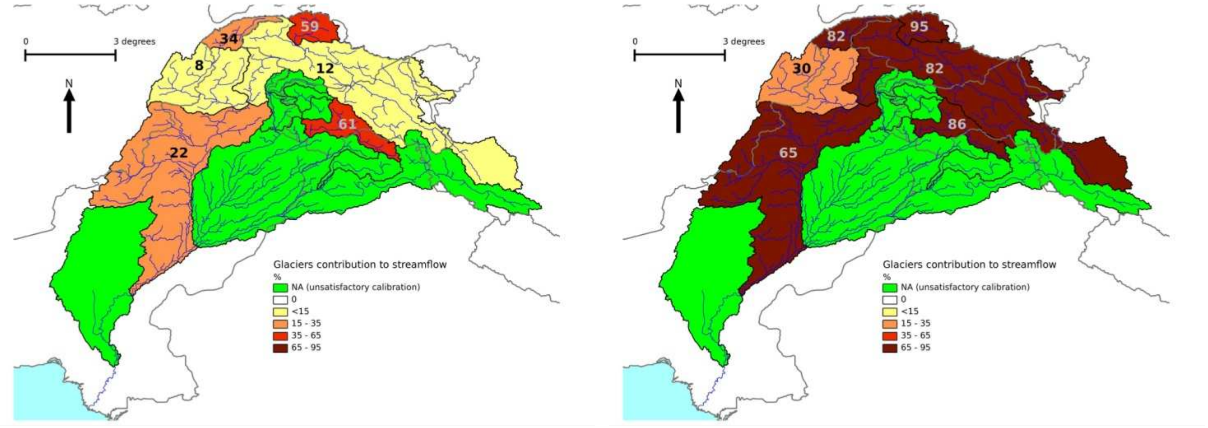
November to January

Figure 3.4. Average contribution of glaciers to annual and seasonal stream flows in the Ganges basin down to Farakka, as simulated for period 1982 to 2002.



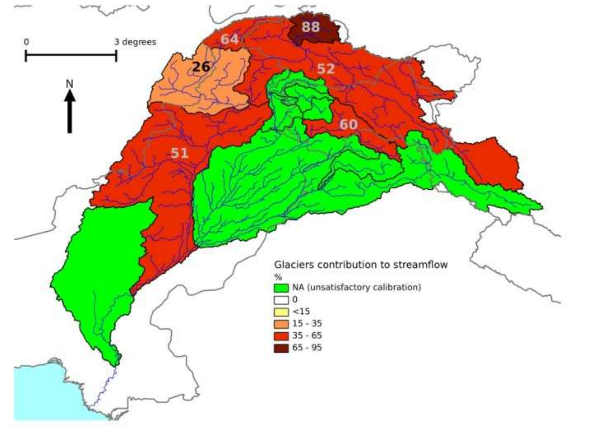
Annual

December to February



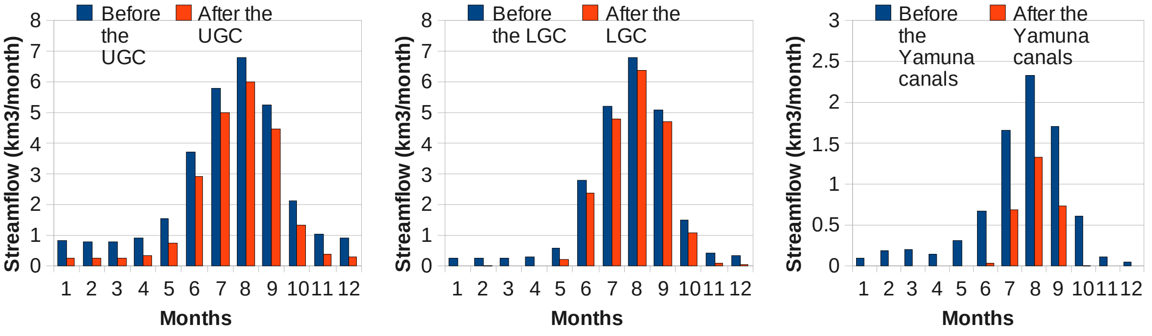
March to May

June to August



September to November

Figure 3.5. Average contribution of glaciers to annual and seasonal streamflows in the Indus basin down to Kotri, as simulated for period 1982 to 2002.



Haridwar, UGC for the Upper Ganga Canal

Narora, LGC for the Lower Ganga Canal

Tajewala

Figure 3.6. Simulated impact of canal withdrawals on the average monthly stream flow in some locations of the Ganges basin, period 1982 – 2002.

3.3. Water Balance Analysis at Sub-basin Level

In order to carry out detailed water resources assessment, three sub-basins were identified within the larger Ganga basin. The three sub-basins representing different areas in Ganges basin are the Koshi, in Tibet and Nepal; the Upper Ganga in India and the Gorai sub-basin in Bangaladesh. The Soil Water Assessment Tool (SWAT) was used to simulate the hydrology and to calculate the water balances in each sub-basin.

3.3.1 Gorai River catchment, Bangladesh

The Gorai River catchment is located in south-west Bangladesh (Fig. 3.7.). The catchment, like the rest of Bangladesh has a monsoon climate with seasonal wind reversal. There are four seasons namely winter (December-February), summer (March-May), monsoon (June-September) and post-monsoon (October and November). The average temperature varies between 22 ° and 23° in the winter and 23° to 30° C in the summer. Average annual rainfall varies between 1,516 mm in the northeast and 2,478 mm in the southeast. More than 72 percent of the rainfall occurs during monsoon (June-September). Relative humidity is very high and ranges from 77-79% (Bangladesh Water Development Board, 2000).

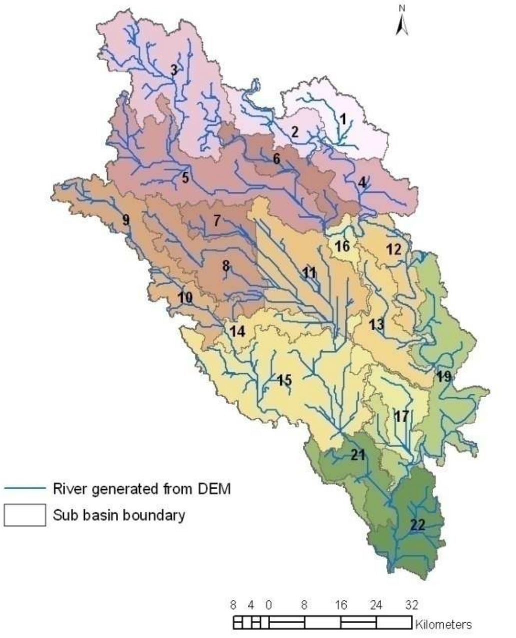


Figure 3.7. Sub-catchments of Gorai River sub-basin, Bangladesh.

3.3.1.1. Water balance: Figure 3.8 presents the average annual water balance calculations for the period from 1965-1975 for each of the sub-basins shown in Fig. 3.7. In the water balance calculations four hydrological components are considered i.e. rainfall (RF), evapo-transpiration (ET), runoff (RO) and balance closure. The term 'balance closure' comprises groundwater recharge, change in soil moisture storage in the vadoze zone and inflow coming from Ganga as well as model inaccuracies. As the inflow from the Ganga is a dominant factor in the water balance of the sub-catchments in the Gorai, runoff values can be seen to be higher especially from the sub-basins receiving water directly from the inlet. Average annual precipitation from all the sub-basins from 1965-1975 was 1700mm. ET values were relatively high for the basin. The average annual ET for the 10 year period was 1,527mm. The highest ET was calculated from sub basin 22 which can be mainly attributed to the presence of extensive water bodies. Average runoff for the modeling period was calculated as 714mm. This runoff value however, is the routed runoff so includes the inflow coming from upstream.

Figure 3.9 presents the water balance calculations for the period from 1990-1997. Average annual rainfall (RF) for all the sub-basins was calculated as 1,741mm and actual evapo-transpiration (ET) is again high with average annual values of 1,402 mm. The average annual runoff was calculated as 188mm, which is 26% less than the average runoff for the time period from 1965-75. Reduction in inflow into the basin from the main Ganges River as discussed in earlier sections is the most obvious reason. However, changes in land use also had an effect in the catchment hydrology and are especially reflected in the changes in ET. From the analysis, it was found that ET has decreased in many sub-basins where land cover has changed from forest to agriculture and increased where rice has replaced some of the traditional agricultural crops.

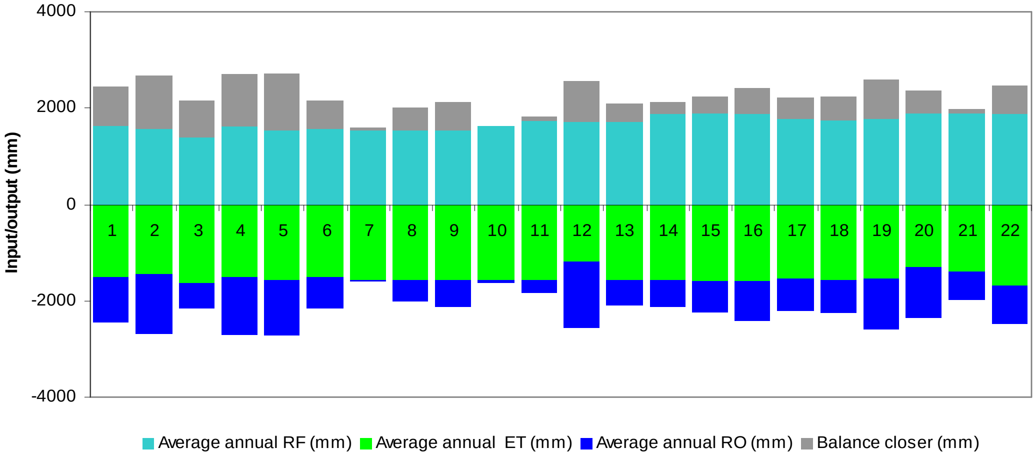


Figure 3.8. Water balance at each sub basin during 1965 to 1975 (1 to 22 are sub basin numbers as seen on Fig. 3.7).

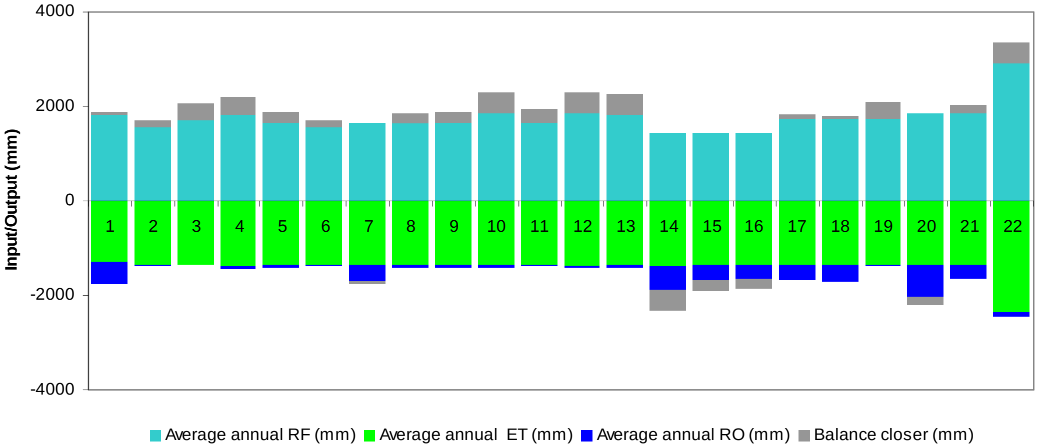


Figure 3.9. Water balance at each sub basin during 1990 to 1997 (1 to 22 is sub basin number as seen on Fig.3.7.).

3.3.1.2. Change in inflow into the catchment: Figure 3.10 shows the average monthly inflow to the Gorai catchment for the period from 1965-1975 and 1990-1999. Analysis of flow from this station is important because it is the main supply of water from the Ganges into the Delta region of southwest Bangladesh. As can be seen from the figure, there is reduction in flows in both the monsoon and dry seasons. The reduction in flows in the dry season is a more critical problem for agriculture as during the monsoon season (June-September) rainfall is adequate. Irrigation is required during the rabi (a cropping season spanning over November-May) and especially during February and March for rice cultivation (bow rice crop is usually planted in January-February and harvested in April-May). In our analysis, we found that the average flows in February and March in the period from 1965-1975 and from 1990-1999 were 17MCM and 2 MCM, respectively. Reduction in inflow can be attributed mainly to upstream water regulation and development which includes the Farakka barrage but also the water withdrawals in the river stretch downstream Farakka in India and as well as Bangladesh.

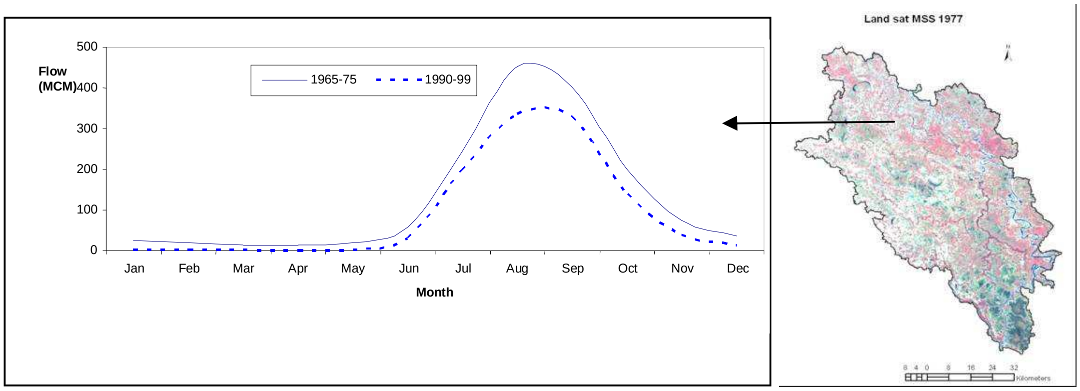


Figure 3.10. Effect of land use changes on average monthly inflow to the Gorai Catchment, Bangladesh.

3.3.2. Upper Ganga catchment, India

The River Ganga rises in the Gangotri glacier in the Himalayas. The Upper Ganga sub-basin was delineated by using the 90m SRTM digital elevation map with Kanpur barrage as the outlet point (Figure 3.11(a). The elevation in the sub-basin ranges from 7,500 m at upper mountain region to 100 m in the lower plains and the total area is 87,000 km^2.Some mountain peaks in the head water reaches of the river are permanently covered with snow. Rainfall in the sub-basin was found to range between 200 and 2,200 mm. A major part of the rains is by the south-western monsoon from July to October.

Figure 3.11(a). Upper Ganga sub-basin till Kanpur, India.

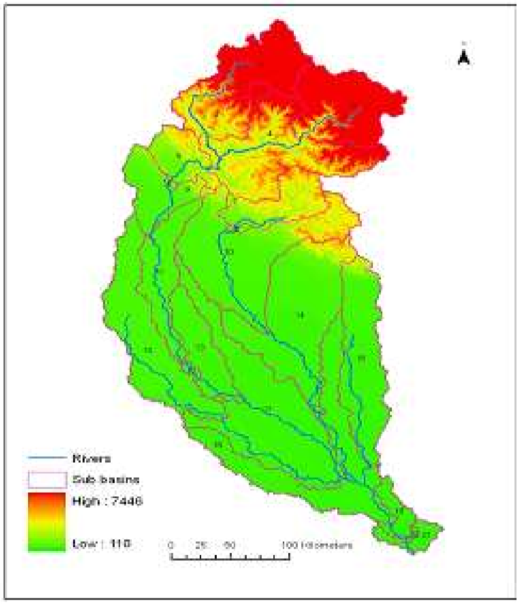


Figure 3.11(b). The main rivers and canal system in the Upper Ganga sub-basin.

The main river channel is highly regulated with dams, barrages and corresponding canal systems (Figure 3.11 (b). The two main dams are the Tehri dam and the Ramganga dam. In this study however, only the Ram ganga dam was considered as the Tehri dam became operational after the study period (study period is from 1995-2005). There are three main canal systems. The Upper Ganga Canal takes off from the right flank of the Bhimgoda barrage with a head discharge of 190 cumec and presently, the gross command area is about 2 million ha. The Madhya Ganga canal takes off from the Ganga at Raoli barrage near Bijnor and provides annual irrigation to 178,000 ha. The Lower Ganga canal comprises a weir across the Ganga at Naraora and irrigates 500,000 ha.

The water balance calculations can be seen in Figure 3.12 for the sub-basins in the catchment. The sub-basin distribution, with numbers can be seen in Figure 3.13. Rainfall, ET and water yield was found to be higher in the upper catchments. Water balances from the lower part of catchment, especially runoff are affected by water regulation through the barrages, dams and canals.

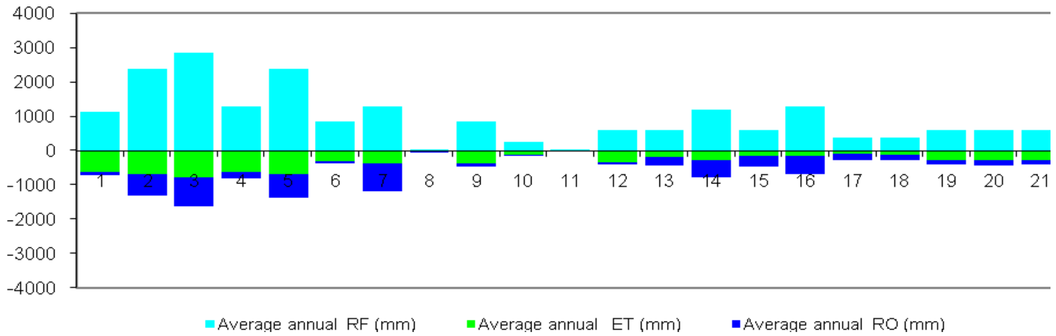
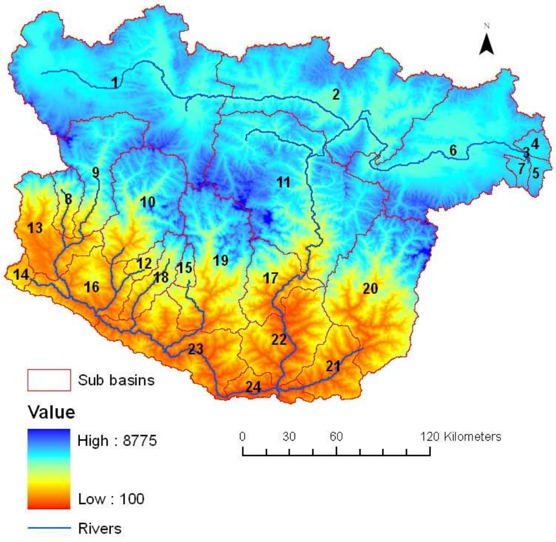


Figure 3.12. Average annual water balances which include Rainfall (RF), Evapo-transpiration (ET) and Runoff (RO) from sub-basins within the Upper-Ganga catchment.



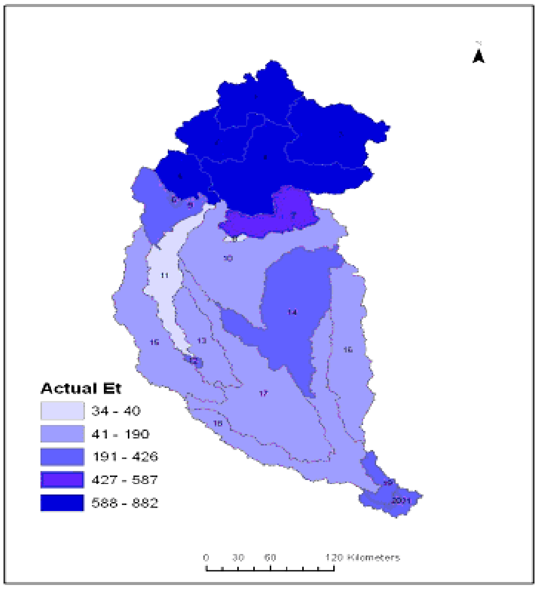


Figure 3.13. Distribution of sub-catchments in Upper Ganga sub-basin.

Figure 3.14. Variation of actual evapo-transpiration (mm) in the sub-catchments of Upper Ganga sub-basin.

The large network of canals transfer water from one sub-basin to irrigate another sub-basin therefore, it is difficult to know whether the runoff calculations from each sub-basin are precise however the ET and rainfall figures from calculation are useful in characterizing the water availability and use in each of the sub-basins. ET (Figure 3.14) is found to be highest for the forested areas followed by irrigated areas.

3.3.3. Koshi catchment, Nepal

The area considered in this study is the Koshi Basin upstream of Chatara in the mountainous region of eastern Nepal and southern Tibet. The study area includes the entire mountainous region in the Koshi Basin and is characterized by high climatic and geographical variability. The average elevation of the basin is 3,800 m but varies from 140 m at Chatara to more than 8,000 m in the Great Himalayan Range including Mount Everest (8,848 metres, world's highest peak).
The modelling period was from 1996 till 2005. The calibration period was from Janauary, 1996 to December, 1997 and the validation period was from January, 1998 to December, 2000.

Figure 3.15 presents the water balance calculations for the Koshi catchment. As can be seen from the figure, the southern part of the basin is wetter than the trans-Himalayan northern part of the basin. Evapo-transpiration is higher in the south than in the north and runoff exceeds evapo-transpiration in the southern part of the catchment.

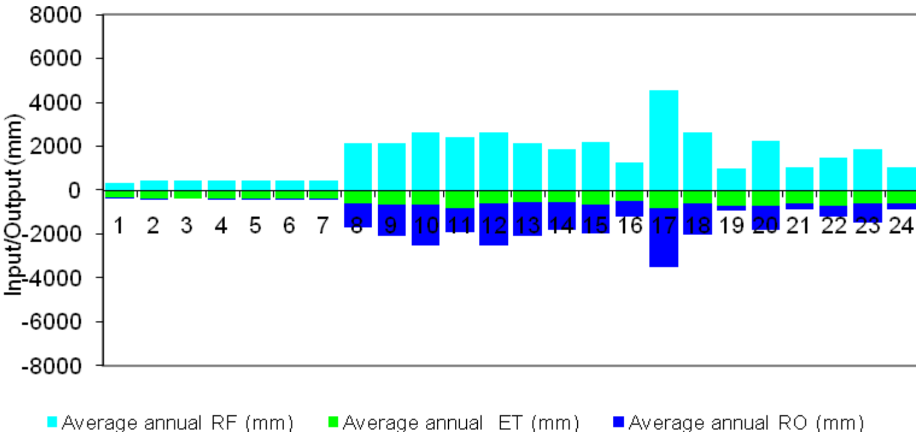


Figure 3.15. Water balance calculations for sub-basins of the Koshi catchment.

3.4. Threats to Future Availability of Water Resources

3.4.1. Impact of climate change on water resources availability

The report by Christensen et al. (2007) from the Inter-governmental Panel on Climate Change (IPCC) indicates that in the Tibetan region the temperature increase at the end of the century could be +3.8 °C. ICIMOD (2009) provides information of the same order. Therefore, this trend was considered to analyze with the WEAP applications in the Indus and Ganges basins scenarios of increase in temperature. More precisely, the following three scenarios were considered:

i. An increase of 1°C after 20-years, i.e., a rate of +0.05°C/year,
ii. An increase of 2°C after 20-years, i.e., a rate of +0.10°C/year,
iii. An increase of 3°C after 20-years, i.e., a rate of +0.15°C/year.

This last scenario should be considered as the extreme scenario. In each scenario, the temperature was increased gradually every year.

Impact on annual stream flow logically decreases from upstream to downstream; as (*i*) contribution from rainfall dilutes flows from glaciers, and (*ii*) increased temperature also produce greater evapo-transpiration in the plains hence less stream flows (Table 3.6). The amount of extra flows is rather insignificant downstream at Farakka but not upstream, as for instance in the Upper Ganges at Haridwar and Narora, or in mountainous sub-basins (e.g., Tehri dam).

Table 3.6. WEAP-simulated average change in annual stream flow in some locations of the Ganges basin when temperature increased gradually over 20 years, as compared to the reference scenario (period 1982 to 2002).

Scenario	Average change in annual stream flow, km^3/year at					
	Tehri dam	Haridwar	Narora	Tajewala	Delhi	Farakka
+1°C over 20 years	+0.6 (+8%)[a]	+1.9 (+6%)	+1.8 (+8%)	+0.2 (+2%)	negligible	+4.2 (+1%)
+2°C over 20 years	+1.2 (+17%)	+3.9 (+13%)	+3.6 (+15%)	+0.3 (+4%)	negligible	+8.8 (+3%)
+3°C over 20 years	+1.9 (+26%)	+6.0 (+20%)	+5.4 (+23%)	+0.4 (+5%)	negligible	+13.4 (+4%)

[a] *Percentage values in parenthesis are the variation compared to the reference scenario*

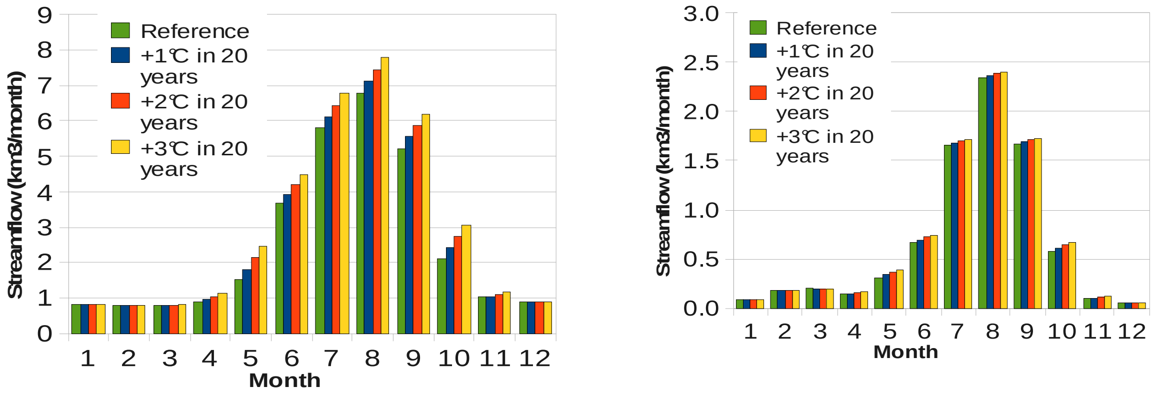
Figure 3.16 shows the simulated impact on monthly flows in some locations of the Ganges basin. As glaciers' contribution is mainly during the high flow season, the increase in flow also occurs predominantly during the high flow season (May to October). Contribution from glaciers starts earlier (April – May) and ends later (October – November) although there is hardly any modification during the low flow season. If we refer to the magnitude presented in Table 3.6, such increase in temperature may create flood events more frequently or of higher magnitude, whether in Upper Ganges or in mountainous sub-basins (e.g., Devghat and Tehri dam).

Tendencies of stream flow changes are similar in the Indus basin but of a greater magnitude due to higher contribution from the glaciers and ice melt. Even with 1° C, the flows at both Tarbela and Sukkur barrage increase nearly by 10 percent and much higher with higher temperature increases. As such, annual increase of stream flows is significant (Table 3.7) and risks of additional floods become predominant, especially at Sukkur barrage (Figure 3.17).

Table 3.7. Simulated average change in annual streamflow in some locations of the Indus basin when temperature increased gradually over 20 years, as compared to the reference scenario of 1982-2002.

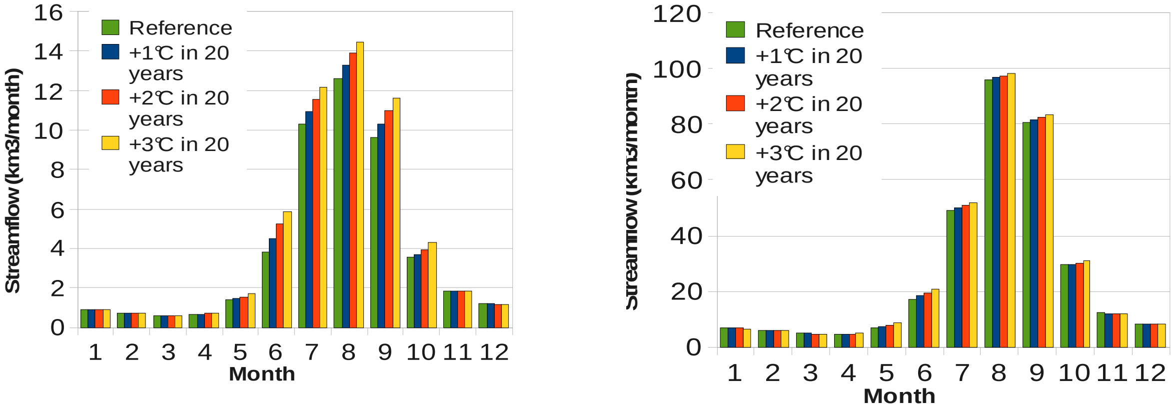
Scenario	Average change in annual stream flow, km^3/year	
	Inflow to Tarbela dam	Flow at Sukkur barrage
+1°C over 20 years	+6.6 (+9%)[a]	+8.1 (+10%)
+2°C over 20 years	+15.2 (+21%)	+18.4 (+22%)
+3°C over 20 years	+22.6 (+31%)	+28.5 (+34%)

[a] Percentage values in parenthesis are the variation compared to the reference scenario (period 1982 to 2002).



a. Haridwar, before canal withdrawal

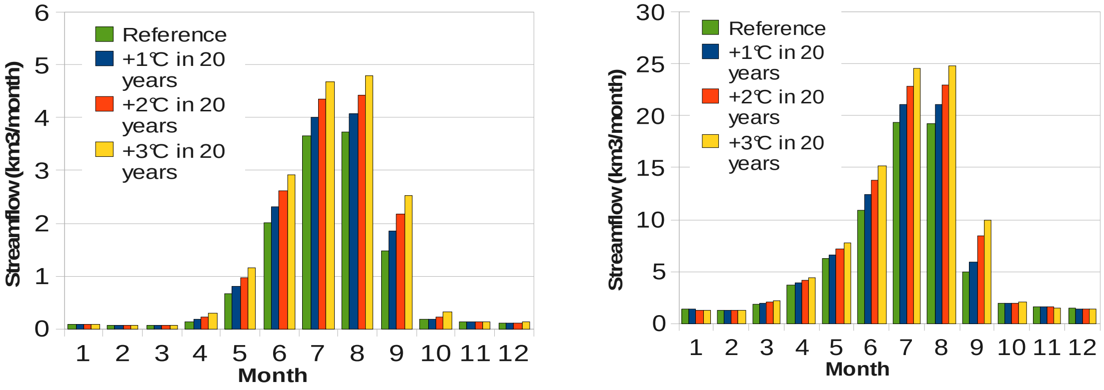
b. Tajewala, before canal withdrawal



c. Devghat

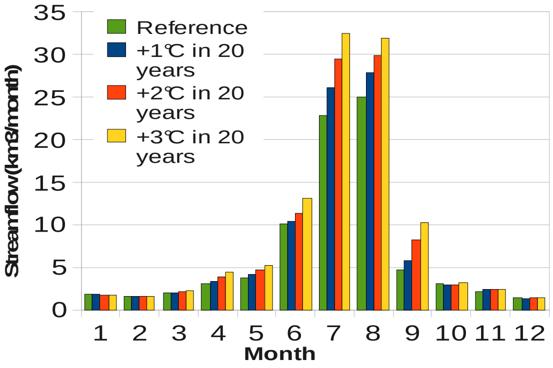
d. Farakka

Figure 3.16. Simulated impact on average monthly streamflows in some locations of the Ganges basin (a. Haridwar, b. Tajewala, c. Devghat d. Farakka) of a gradual increase in temperature over 20 years, as compared to the reference scenario (period 1982 to 2002).



a. Danyour bridge

b. Tarbela dam



c. Sukkur barrage

Figure 3.17. Simulated impact on average monthly stream flows at some locations (a. Danyour bridge, b. Tarbela dam c. Sukkur barrage) of the Indus basin of a gradual increase in temperature over 20 years, as compared to the reference scenario (period 1982 to 2002).

In terms of water uses, this extra water from glaciers does not flow when the water is most required, i.e., during the low flow periods. Nevertheless, making best use of this extra water may make sense as, for instance, the Upper Ganga canal currently withdraws about 6 km3/year at Haridwar, which is about the same order of extra water at Haridwar in case the temperature increases. Using this extra water would require the ability to withdraw and use / store this water during the high flows (e.g., at Tarbela dam, Tehri dam, Haridwar, Narora), which is practically difficult seeing the magnitude of the high flows. Nevertheless, probably the increased flows in April - May could be the most beneficial in term of water uses as this is just after the dry season and it is probably possible to capture the magnitude of this extra flow from the glaciers. This extra flow during April-May may also be used for recharge of over-exploited aquifers through large Manager Aquifer Recharge Projects in the two basins.

4. WATER PRODUCTIVITY IN THE INDUS-GANGETIC BASIN

Cai Xueliang, Bharat R. Sharma, S Hervas, M.G. Khan, M.G. Mustafa, M. Alauddin

4.1. Water Productivity and its Estimation at the Basin Scale

The world needs to ensure higher and sustainable land productivity to meet the rising food demand, changing diet patterns, and the bio-fuel consumption. Among the many factors affecting land productivity, e.g., soil, seed, fertilizer, insects and diseases, machinery and power; water is one of the key constraints to be tackled. With the ever competitive demand from industry, domestic uses and eco-system, agricultural sector is restrained to get less water allocation despite the increasing pressure for more food production (Rosegrant et al., 1997). Both the increasing food demand and decreasing water allocation suggest that the agricultural sector has to produce more food with less water, that is, to substantially improve the water productivity (WP) of agriculture.

The level of water use differs significantly across regions, farming systems, canal command areas, and even farm plots. It is not quite clear how water is better used by crops hence contributing to improved productivity in response to different interventions, especially in large river basins across countries. To measure the effectiveness of these interventions, water accounting and water productivity analysis are required to understand the system water input – agricultural output relation. Agricultural WP is the physical mass of production (e.g., biomass, grain yield) or economic value of production to quantum of water used or delivered for the production (Molden, 1997). It measures how the system converts water into goods and services. The generic equation is:

$$WP\ (kg/m^3\ or\ \$/m^3) = \frac{Output\ derived\ from\ water\ use\ (kg/m^2\ or\ \$\ /m^2)}{Water\ input\ (m^3/m^2)} \qquad (1)$$

Output derived from water use includes physical measures, e.g., crop yield, biomass, fish, and livestock production which are all expressed in unit of kilogram; it can be also be expressed in economic values (e.g., dollars) like market value of grain yield and/or biomass or nutritional values (kilocalories). Water input can be gross inflow, net inflow, available water, irrigation, and actual evapo-transpiration.

Scale is a crucial issue in WP studies. Talking about WP without considering appropriate scale is of little value. The main reason for consideration of the scale parameters is water reuse(s). The outflow from one farm/system might be input to another farm/system, which is a natural phenomenon of agricultural system and particularly, of irrigated areas. Scale issue is also of particular interest to different stakeholders in the system from farmers to policy makers. For farmers, they expect better WP at field scale so they can pay less water fees, and get more income. For irrigation managers, they care more about canal command area WP. And for policy makers, the maximum outputs from efficient use of all available water are the key issue. As pursuit of 'maximum outputs from the system' is often the research focus, balancing the benefits of all stakeholders are always important to ensure sustainable development.

Water productivity indices are scale dependent because the input parameters are scale dependent. The gross/net inflow, irrigation application, available water are all calculated within pre-defined boundaries. As a result field level water productivity is usually presented as production mass per volume of applied water (kg/m^3). At the basin level yield of single crop can still be used to compare differences within the basin. As a number of crops are concurrently cultivated in the basin the output is better expressed as the economic value of all agricultural products. The water input at basin level is difficult to measure (even estimate) because of return flow reuses. Instead, the crop consumptive use of water (evapo-transpiration, ET) is the consequence of all ground agricultural water management. The water input is hence better represented by basin evapo-transpiration. The water productivity at basin level is then calculated in terms of value of crops per unit of evapo-transpiration (generally expressed as US$/$m^3$).

Our analysis aimed at basin level agricultural WP assessment with focus on rice-wheat cropping system. An innovative approach was developed by integrating remote sensing, census and weather data to assess crop productivity, crop consumptive water use, and crop WP at basin level. The productivity, ET and WP maps were produced for rice and wheat, separately. The magnitude and variation of WP, the causes for variations, and the scope for improvement was then analyzed. Historical evolution of water productivity changes in rice in Bagladesh was also analyzed. In another study, a framework for estimating the WP of different fisheries systems (capture and culture) was developed and WP of the fisheries estimated for the real systems available in the Gorai sub-basin (Bangladesh).

4.2. Water Productivity of Rice-Wheat Cropping System in Indo-Gangetic Basin

Agricultural intensity in IGB is extremely high. More than 50% of the catchment area is cultivated. Rice-wheat rotation is the predominant cropping system, mixed with cotton, sugarcane, pulses, oilseeds, millet and jute, etc. Figure 4.1 illustrates the estimated percentage cultivated areas of major crops at annual basis in the Indian part of the basin. The percentage of rice and wheat cultivation are 32.3% and 27.5% respectively, both are more than half of the cultivated areas at any single season. The production system of rice-wheat cultivation is of significant importance to food security and household income in the basin. Both crops heavily rely on irrigation and have high demand on better water management interventions. WP of rice-wheat cropping system is, therefore, the focus of this assessment.

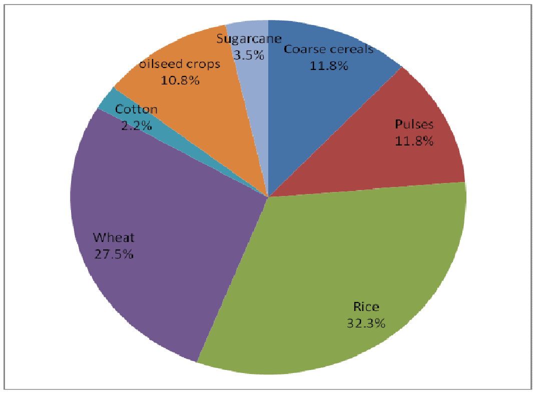


Figure 4.1. Percentage of crop cultivated areas for year 2005-06 in the IG basin.

4.2.1. Physical water productivity of rice (kg/m^3)

The rice productivity, rice ET and rice WP maps for year 2005 derived through an innovative methodology by integrating remote sensing, national census and weather data are shown in Figure 4.2. The average rice yield for Pakistan, India, Nepal and Bangladesh parts of the IGB are 2.60, 2.53, 3.54 and 2.75 t/ha, respectively. However, tremendous differences exist in different areas of the basin. The Indian Punjab state with some adjacent areas from Haryana and Rajasthan states (red patch in Figure 2 rice yield map) has an average yield of 6.18 t/ha, which is significantly higher than that in most other areas within the basin. The low-yield rice areas are also mainly found in the Indian states of Madhya Pradesh, Rajasthan and Bihar with average yields of 1.18, 1.49 and 2.04 t/ha, respectively. This explains the reason for the low average yield of India. With the spatially explicit map of rice yield presented for each pixel, significant variability is also observed at the local scale. For example, the average yield of Indian Punjab is 6.18 tons/ha; yet, it has around 1% area with a relatively low yield of less than 3 t/ha. Although the average performance in Bihar, India is very poor, it has a relatively high yield area (4 t/ha) in a 37 km-diameter circle centered at 25.4N, 84.44E (southwest of Bhojpur district).

The rice ET$_a$ map and the histogram distribution are shown in Figures 4.2 and 4.3, respectively. The seasonal average paddy rice ET$_a$ from June 10th to October 15th, 2005 is 416 mm, ranging from 167 to 608 mm with a standard deviation of 104.6 mm (1% points were sieved). The average value is significantly less than the reference ET (558 mm) and the rice potential ET (610 mm). The average ET for non-rice croplands of the same period is 345 mm, with a slightly higher standard deviation of 109.4 mm.

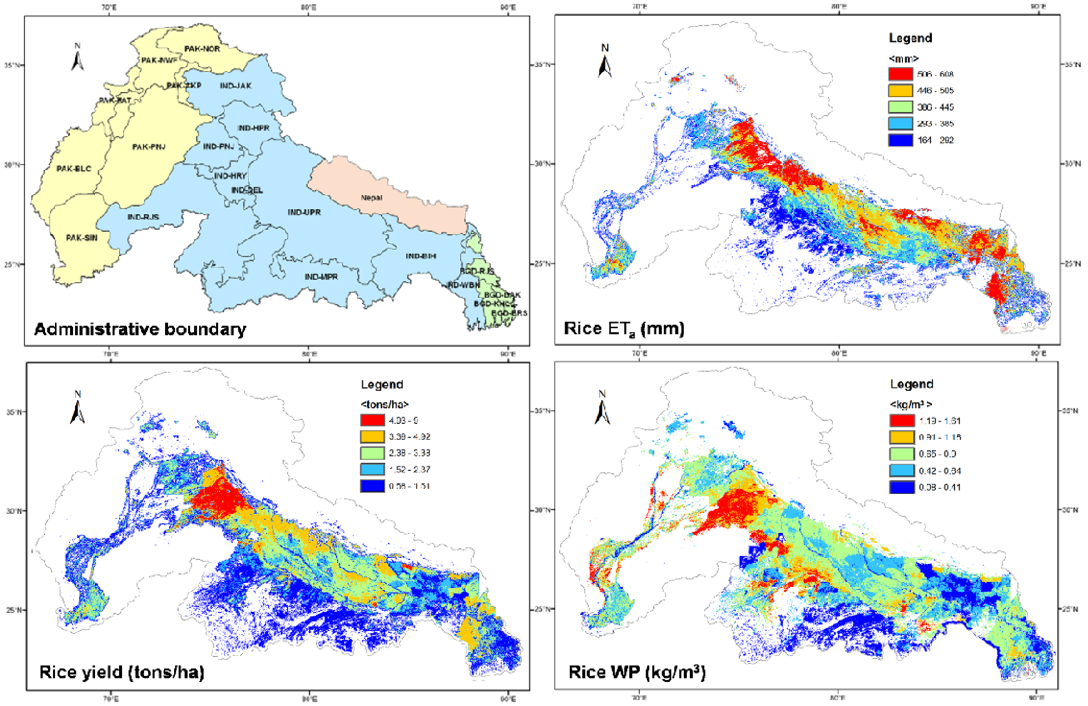


Figure 4.2. Administrative boundary, ET_a, yield and water productivity of rice in the IGB for year 2005.

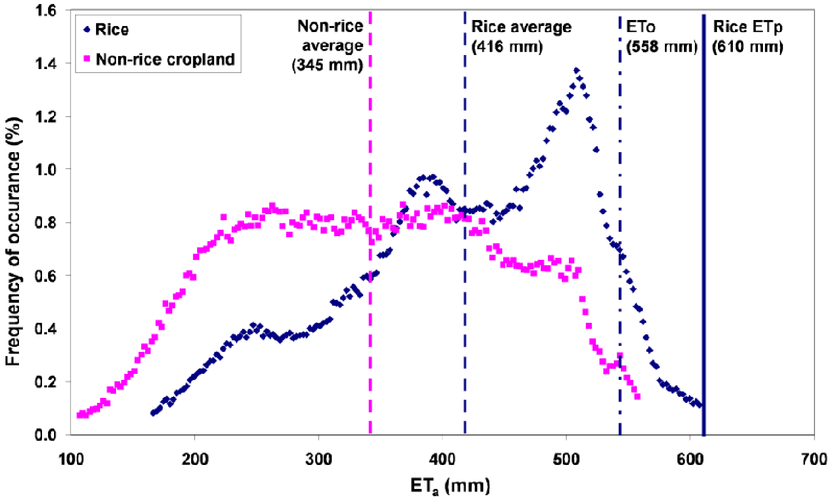


Figure 4.3. The histogram distribution of rice and non-rice cropland ET in IGB for the period of 10 June - 15 October 2005.

Significant variation of ET is observed in Figures 4.2 and 4.3. The adjoining area of the Indus and Ganges catchments in Punjab, Haryana and west Uttar Pradesh, India, covering 7.9% of the total rice area, has the highest evapo-transpiration with an average value of 551 mm. The northern part of West Bengal also has a high ET of 528 mm. A high-ET belt occurs from the Khulna division of Bangladesh to the Indian states of West Bengal, northern Bihar, central Uttar Pradesh, Haryana and Punjab (see Figure 4.2). Low ET areas are mainly found in the Indian states of Madhya Pradesh and Rajasthan, which are far from the main stem of the Ganga River, and the southern part of Punjab and the northern part of Sind provinces in Pakistan, where more mixed cropping pattern is observed. Overall, the ET variations displayed similar trends as shown by yield, although in parts of Bihar state the relatively high ET is accompanied by low yield.

The average rice WP for the basin is 0.74 kg/m^3, with minimum, maximum and standard deviation values of 0.18, 1.8, and 0.329 kg/m^3, respectively, (1% extreme pixels sieved). The WP variation generally closely follows the pattern of yield variation. The Indian Punjab and adjoining areas, covering 6% of the total rice area, have a very high WP with an average value of 1.32 kg/m^3. However, as much as 23% of the total rice areas have a WP less than 0.5 kg/m^3 occurring mainly in Madhya Pradesh and Bihar states of India and the Dhaka division of Bangladesh.

Some areas show different trends in WP variation compared to the yield and ET maps. A high WP strip, around 10-70 km in width, originates from 75.5E, 29N in the southern Haryana state and goes towards the east till the southern Bihar state, India (85.2E, 24N). The yield for this area is relatively low with an average value of 3.2 tons/ha. However, the average ET of the same area is as low as 316 mm, making the WP relatively higher. Possibly, this stretch has the largest area under rainfed rice, where monsoon rains are able to only partially meet the rice ET needs. The higher WP values here do not suggest a satisfactory performance in this case. Rather, it provides interesting clues to reveal the reasons for the differences, the potential for yield improvement or ET reduction, and the possible interventions by “scaling up” to other areas.

4.2.2. Physical water productivity of wheat (kg/m^3)

The wheat productivity, ET and WP maps (Figure 4.4) are produced following the same approach as described for rice. The average wheat yield is 2.65 t/ha for the basin with a high standard deviation of 1.0 t/ha. Overall yield distribution shows similar trend as rice yield does. The bright spots, with an average yield of 4.4 t/ha, appear in the Indian Punjab and Haryana states, with relatively lower values in the upper stream of Indus of Pakistan part and Indian states of Uttar Pradesh (west part) and Rajasthan (North-east part). The hot spots, with yield as low as 0.70 to 1.58 t/ha, appear in Indian Bihar state, part of West Bengal and Bangladesh. However the bright spot of wheat stretches towards southeast along the border of Uttar Pradesh and Madhya Pradesh states. Both rice and wheat heavily rely on irrigation. The difference in yields is likely caused by other factors, soil and fertilizer and crop variety for example rather than water input.

The average wheat evapo-transpiration over the main wheat growth period from November 24, 2005 to April 14, 2006 is 299 mm with standard deviation of 61mm. Wheat ET follows closely the same variability patterns of yields. Highest values were observed at the bright spots of high wheat yield areas. Other areas display relatively low and uniform values.

The average WP of wheat is 0.94 kg/m^3 with standard variation of 0.66 kg/m^3. Due to the extremely low ET in Rajasthan and Madhya Pradesh states, water productivity in these areas show higher values despite low yield. These states still cultivate low yielding traditional wheat varieties which incidentally have high cooking quality and fetch premium price in the market. The growing season in these states is also of shorter duration due to shorter winter period and early maturity of the crop. The high yield areas showed high water productivity values although they are not among the highest. The Bihar State in India has the largest areas with lowest WP, which means significant scope form improvement exists here. The downstream of Ganges shows relatively good performance despite high variability in yield

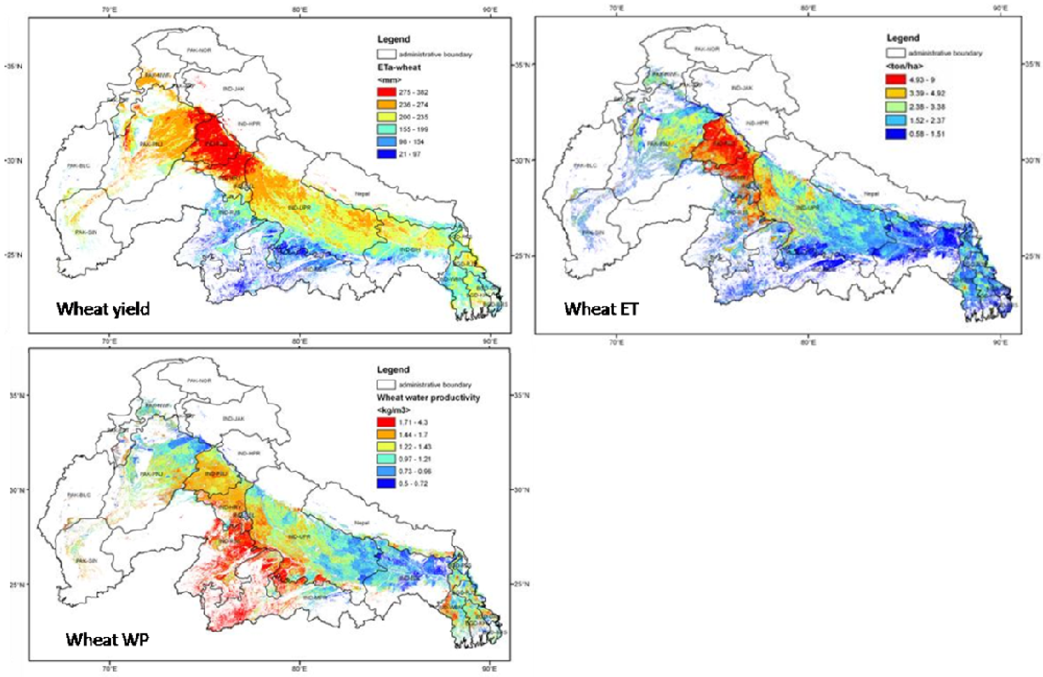


Figure 4.4. Yield, ET_a, and water productivity of wheat in the IGB for year 2005-06.

4.2.3. Variation in water productivity of rice in Bangladesh

Average and marginal water productivity of rice in Bangladesh were estimated by employing district-level time series data involving 21 districts, over a thirty-seven year period of 1968-2004.

District-level growth in average water productivity: The compound annual growth rates of water productivity for the annual (ANUALGR), kharif (KHARIFGR), and rabi (RABIGR) rice crops were estimated. KHARIFGR was much higher than RABIGR. Only three districts experienced kharif growth rates lower than 1.5 per cent per annum.

i. RABIGR for Barisal, Patuakhali, Chittagong, and Chittagong Hill Tracts was not statistically significant. No district experienced annual compound growth rates of 1 per cent while only four districts registered annual growth rates above 0.7 per cent.
ii. ANUALGR in rice water productivity exceeded 1 per cent only in three districts. In six other districts, it ranged between 0.8 and 1.0 per cent.
iii. The eight Ganges Dependent Area (GDA) districts as a whole registered higher growth rates than the thirteen Non-GDA (NGDA) districts taken together for the kharif and annual crops of rice while their combined growth was lower than for the remaining districts for the rabi crop.

The study did not find any statistically significant correlation between the seasonal growth rates ($r = 0.179$, $p<0.439$). However, both the seasonal growth rates were significantly positively correlated with ANUALGR ($r = 0.683$ with KHARIFGR, $p<0.001$; and $r = 0.699$ with RABIGR, $p<0.001$).

Marginal productivity of water in rice production (MPP): MPP, defined as the rate of change of rice crop output (kilogram) due to an m^3 change in consumptive water use (CWU) for each year, was obtained as:

$$QCROPit = \alpha + \beta_{it} CWUit + \varepsilon.$$

where, $QCROPit$ and $CWUit$ respectively represent the crop output and consumptive water use for i^{th} crop of rice across all districts in a given year t. The βs represent MPPs of the relevant rice crop in year t. The following observations (Table 4.1) were made:

i. MPP of *kharif* rice crop (KHARIFMP) has always been lower than that for the *rabi* (RABIMP) and annual rice (ANUALMP) crops. This is possibly due to the faster pace of adoption and deeper penetration of the HYV technology during the *rabi* season.

ii. Of the three phases (1968-1980; 1981-1990; 1991-2004), the average first phase level KHARIFMP is quite low in absolute terms (289g/ m^3 increase in CWU), which declined in the second phase but increased in the third phase (Table 4.1). Relative to the first phase KHARIFMP increased by 38 per cent in the third phase recovering from a 20% decline (to 231g.) in the second phase. Over the entire sample period of thirty-seven years, KHARFMP has remained much the same as that in the first phase.
iii. RABIMP increased only about 16 per cent in the first phase (from 345g to 399g). However, it increased by more than 60 per cent to 556g in the third phase relative to that in the first phase.
iv. For the annual crop, MPP (ANUALMP) remained stagnant (at about 300g) during the first two phases but increased by about 45 percent (to 437g) in the third phase.

Data under Table 4.2 presents compound annual growth rates based on semi-logarithmic trend corrected for autocorrelation by the Cochrane-Orcutt method. The following patterns seem to emerge:

i. Over the thirty-seven year period, KHARIFMP, RABIMP, and OVERALLMP registered growth rates of about 2%, 0.5% and 0.76%, respectively.
ii. In the first phase (1968-1980), KHARIFMP grew at an annual rate close to 3 per cent, while RABIMP did not experience any statistically significant trend. ANUALMP grew at a statistically significant *albeit* much slower rate of 1.13%.
iii. In the second phase (1981-1990), growth rate in KAHRIFMP declined to just over 1.7% with RABIMP registering no statistically significant trend. The ANUALMP recorded a slightly higher growth rate compared to the first phase.
iv. In the third phase (1991-2004) growth rates in all three MPPs picked up quite significantly. RABIMP growth staged the most significant recovery growing nearly at 1% per cent per annum. This can be partly explained by the growth of tubewell irrigation for *boro* rice during this period.

Table 4.1. Marginal physical product (MPP) of water in rice production (g per m^3 increase in CWU), in Bangladesh during selected sub-periods.

Sub-period	KHARIFMP	RABIMP	ANUALMP
1968-1980	289	345	302
1981-1990	231	399	305
1991-2004	399	556	437
1968-2004	285	519	297

Table 4.2. Compound growth rates in marginal productivity of water in rice production for selected sub-periods.

Period	Compound growth rates (per cent per annum)		
	KHARIFMP[a]	RABIMP[a]	ANUALMP[a]
1968-1980	2.978	Statistically insignificant	0.610
1981-1990	1.734	Statistically insignificant	0.689
1991-2004	2.545	0.957	1.131
1968-2004	1.992	0.497	0.764

[a] *Calculated following the same method as described in Table 4.1. All growth rates are statistically significant unless otherwise indicated.*

Spatial variation of marginal water productivity of rice in Bangladesh: MPP of rice across districts using the corresponding output-CWU combination obtained from the below equation, corrected for auto-correlation using the Cochrane-Orcutt method:

$$QCROPip = \alpha + \beta CWUip + \varepsilon.$$

where ,$QCROP_{ip}$ and CWU_{ip} respectively represent the crop output in g and consumptive water use for i^{th} rice crop in all years for the p^{th} district. The βs represent MPPs of the relevant rice crop for the respective districts. The following trends were seen:

i. KHARIFMP ranged between 156g (Jamalpur) and 348g (Comilla). For two thirds of the districts it stood below 300g. The best performing districts were Comilla, Noakhali and Chittagong.
ii. RABIMP ranged between 397g (Chittagong) and 682g (Tangail). Five of the twenty-one districts recorded RABIMP level below 500g (Chittagong, Sylhet, Kishoreganj, Chittanong Hill Tracts, and Patuakhali). In three districts (Tangail, Comilla and Pabna) it exceeded 600g. In the remaining thirteen districts RABIMP stood in the range of 500-600g.

iii. ANUALMP ranged between 143g (Jamalpur) and 406g (Chittagong Hill Tracts). The 'top' performers were Chittagong Hill Tracts (406 g), Bogra (375g) and Noakhali (371g).
iv. KHARIFMP and ANUALMP were marginally higher in the non-Ganges dependent group of districts relative to those in the Ganges dependent group. The opposite seems to be the case for RABIMP, which is 11 per cent higher for the GDA districts.

Are there any 'hot spots' and 'bright spots' of rice water productivity in Bangladesh? The pace at which average water productivity has grown over time varies across seasons and differentially impact on the growth in annual water productivity (ANUALGR). Levels of MPPs also differ across seasons. Under these circumstances, a uniform dividing line to identify 'hot spots' and 'bright spots' may not be appropriate. Against this background, Table 4.3 classifies districts as 'hot spots' and 'bright spots' based on compound annual growth rates. For the *kharif* crop, three districts (Jessore, Kushtia and Rajshahi) can be considered as 'hot spots', which have experienced annual growth rates in excess of 2.5 per cent. The 'bright spots' districts are those that have recorded annual growth rates in the 2-2.5 per cent range. Five districts fall in this category. It can be noted that five (Jessore, Kushtia, Rajshahi, Khulna and Pabna) of the eight districts experiencing the fastest growth in average water productivity were from the Ganges Dependent Area.

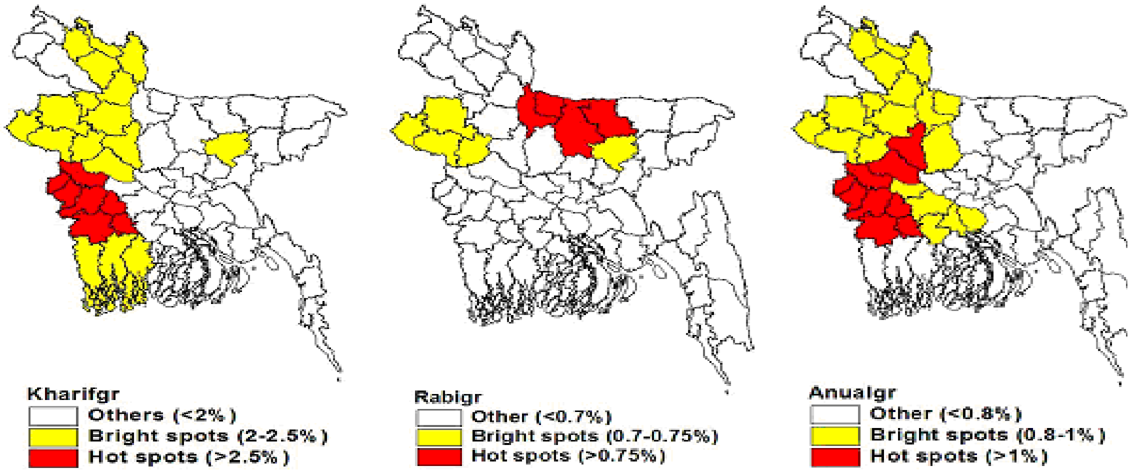
The *rabi* season scenario is quite different in that none of the districts has experienced growth rate in excess of 1 per cent. In such a situation, hot and bright spots are defined as those that have registered annual growth rates in excess of 0.75 per cent and in the 0.7-0.75 percent range, respectively. Only four districts (Jamalpur, Mymensingh, Kishoreganj and Rajshahi) meet these criteria. Of these four districts, only Rajshahi is from the GDA.

For the annual rice crop, yet another criterion is applied. The districts that grew at rates faster that 1 per cent were in the 'hot spot' category while those that grew between 0.8 and 1 per cent constituted the 'bright spots'. Note that five of the nine fastest growing districts in annual rice water productivity are from the GDA. Panels A, B and C in Figure 4.5 respectively identify the 'hot spots' and 'bright spots' for kharif, rabi and annual rice crop water productivity growth rates.

Table 4.3: 'Hot spots' and 'bright spots' in average rice water productivity growth by season.

KHARIFGR		RABIGR		ANUALGR	
Hot spot (≥2.5%)	Bright spot (2.0-2.5%)	Hot spot (≥0.75%)	Bright spot (0.7-0.75%)	Hot spot (≥1.0%)	Bright spot (0.8-1.0%)
Jessore* Kushtia* Rajshahi*	Khulna* Pabna* Bogra Rangpur Kishoreganj	Jamalpur Mymensingh	Kishoreganj Rajshahi*	Jessore* Pabna* Kushtia*	Tangail Rajshahi* Bogra Jamalpur Rangpur Faridpur*

**GDA districts.*



A. Growth rates in average water productivity of kharif rice crop.

B. Growth rates in average water productivity of rabi rice crop

C. Growth rates in average water productivity of annual rice crop

Figure 4.5. 'Hot spots' and 'bright spots' of growth in *kharif, rabi* and annul rice crop average water productivity.

The study also found that water productivity is critically dependent on groundwater irrigation especially in areas where irrigation water is a scarce environmental resource. The increasing water intensity in the production process can be illustrated by Figure 4.6, which depicts a hypothetical representation of the early 1970s and early 2000s of the patterns of environmental capital intensity (proxied by groundwater usage) of agricultural production in Bangladesh. The horizontal axis measures the environmental capital while man-made capital and human labour including human capital as a composite input is measured along the vertical axis. The flatter ray 'OD' typically represents the current Bangladesh scenario as production is more environment-intensive given the high propensity to treat environment (groundwater) as a non-scarce or abundant factor or worse still as a 'free gift' of nature. The steeper ray 'OC' on the other hand depicts a hypothetical initial environment-intensity of agricultural production. Given the fragility of the physical environment, groundwater resources in Bangladesh need to be better valued than at present.

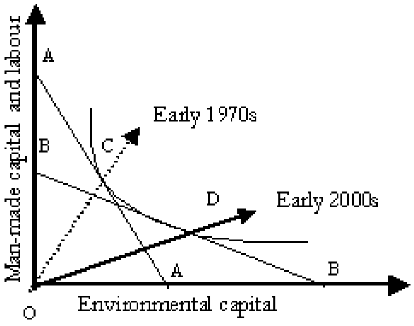


Figure 4.6. Hypothetical scenario portraying current and desirable environmental capital intensity in agricultural production in the context of Bangladesh.

4.3. Annual Economic Water Productivity of Rice-Wheat Cropping System

Water productivity values have been calculated for rice and wheat separately in terms of grain yield production and ET. As observed, the overall variations of WP for the two crops are similar to some degree. Some areas may have less WP for rice but more WP for wheat. It is, therefore, interesting to look at total WP of both crops. To do this the WP values have to be expressed in economic terms to compare and sum the WP of different crops.

The average rice WP expressed in US dollars in 2005 at local market price is 0.121 US $/m^3, while for wheat it is 0.148 US $/m^3. The ratio of rice WP to wheat WP expressed in economic value is slightly higher than that expressed in physical mass production due to higher price at local market for rice.

The average WP for the rice-wheat rotation system is 0.131 US $/m^3 (Figure 4.7). The spatial variation of rice-wheat WP is found to be different both from rice and wheat WP maps. The WP of the border areas of Rajasthan, Madhya Pradesh, and Uttar Pradesh stand out together with Indian Punjab to be the overall best performing areas examined using rice-wheat WP indicator. The shared areas of rice and wheat cultivation are influenced more by wheat than rice due to higher WP of wheat. However, areas with low wheat WP but high rice WP and the other way around are found in many areas. The rice WP contributed 50.7% to the rice-wheat WP due to larger cultivation area despite lower WP values.

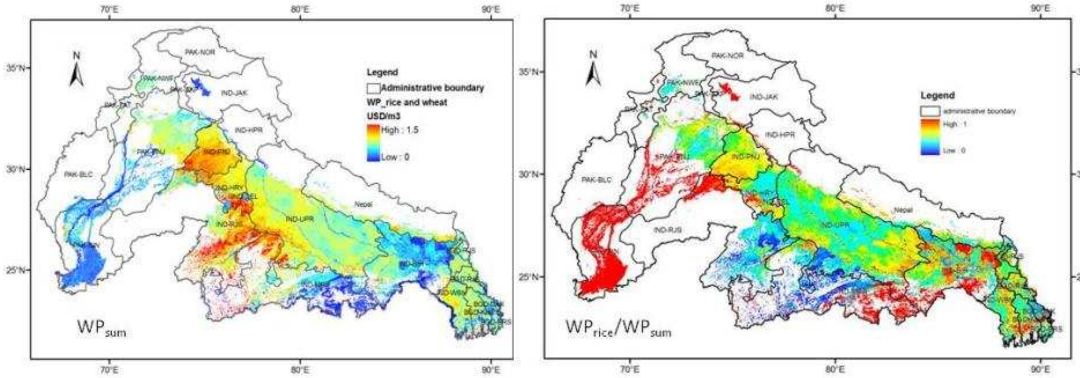


Figure 4.7. Water productivity of rice-wheat rotation system in IGB and the contribution of rice to the rice-wheat system water productivity.

4.3.1. Water productivity of agricultural sector

Agricultural intensity and heterogeneity in Indo-Gangetic river basin are very high largely due to the dense population. Though, rice-wheat rotation is the major cropping pattern, other crops are also cultivated in the basin including sugarcane, oilseed crops, pulses and coarse cereals. The cultivation areas of these crops are relatively small than rice and wheat, but some have high market values hence contribute significantly to the basin WP gains.

The average WP of all kharif crops in Indian part of the basin is 0.191 US$/m^3, which is 158% of that of rice. Figure 4.8 illustrates the distribution of crop WP. As can be observed, the WP of all crops showed very different variation in comparison with rice WP. The "bright spots" are mainly observed in the dry areas, for example, Rajasthan, Himachal Pradesh and Uttrakhand states, where the access to water is poorer and non-rice crops are more important.

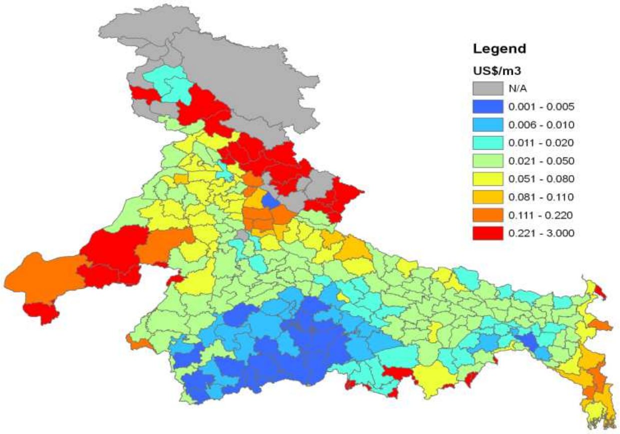


Figure 4.8. Water productivity of all *kharif* crops in Indian part of the Indo-Gangetic basin.

4.4. Factors Affecting Variations in Crop Water Productivity

Crop water productivity values are relatively low with tremendous variation in Indo-Gangetic river basin. These variations could be explained by many factors, for example, soil fertility, water supply, and crop management and climatic conditions. This section aims to explore the factors affecting water productivity in the basin. Figure 4.9 illustrates some important factors affecting water productivity. The rainfall measured from Tropical Rainfall Measurement Mission (TRMM), the land surface temperature, and the ratio of ET_a (actual evapo-transpiration) to ET_p (potential evapo-transpiration) is illustrated separately for rice and wheat. The basin Digital Elevation Model (DEM), groundwater depth of Indian part and main river streams of Indus and Ganges are also compared.

It is observed that overall rainfall during rice growing season (*kharif)* is much higher than that of wheat season (*rabi*). The rainfall in Indus basin is much lower than Ganges basin during rice growing season but higher during wheat season. Land surface temperature variations are similar in both seasons. The highest temperature is observed in the downstream areas of Indus basin where deserts dominant the landscape. And the lowest temperature occurs in the northern mountain areas. DEM shows in main agricultural areas of IGB, the land topography is relatively flat. However, the altitude of southern part of Ganges basin is relatively high. The groundwater depth to the land surface showed an obvious decline from east to the west in the basin. Large areas in Bihar and West Bengal have very shallow groundwater depth. But it becomes very deep in Punjab and Rajasthan.

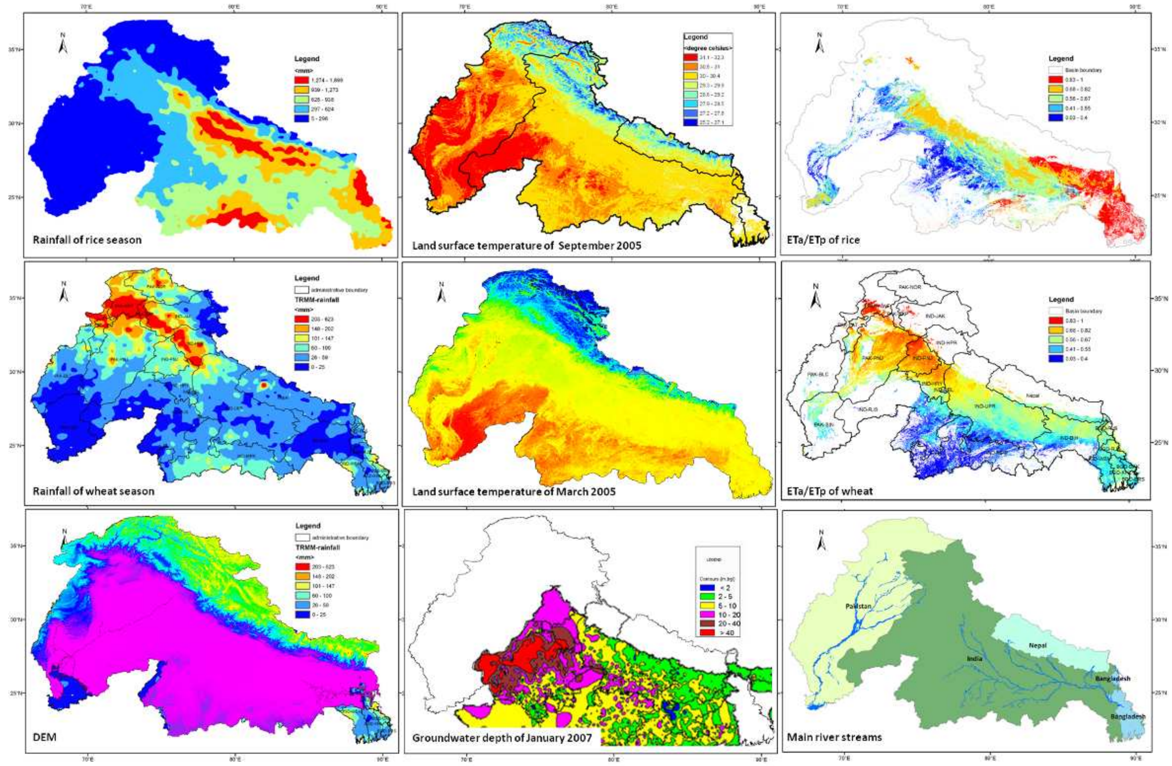


Figure 4.9. Comparison of factors affecting water productivity of rice and wheat in the Indus-Gangetic basin.

Rice performance is somehow in contrast to the distribution of constraining factors illustrated above. It is observed that the rice ET_p is lower in the Ganges basin, which is opposite to rainfall distribution. Significant crop stress (ET_a/ET_p, the lower the ratio the greater the stress) is observed in large parts of the basin, which mainly occur in Indus basin and southern part of Ganges basin. Indus is a closed basin facing severe water scarcity. Further, parts of Pakistan Sind and Punjab provinces have also witnessed significant water stress. The NDVI profiles showed that these areas have much more complicated cropping patterns in comparison to Indian Punjab. The diverse cropping types and growing periods could both lead to low average pixel ET. The Madhya Pradesh and Rajasthan states in southern part of the Ganges basin, where most severe water stress is observed, is located in high elevation and warm areas and far from the main river streams. Rainfall is also low and a large area is rain-fed. The well-performing Indian Punjab showed very little water stress in spite of deep groundwater table and low rainfall. Surprisingly, large areas in the downstream of Ganges also showed a very low water-stress level in contrast to low yields and low WP values. In these areas the rainfall is very high, which is complemented by higher flow rates in the rivers. Shallow groundwater table also directly contributes to higher evapo-transpiration.

However, higher water availability does not necessarily lead to higher yield or WP, as shown in this case. Crop development is linked to land, crop and water management practices. Rainfall may occur at any time; hence the paddy has more standing water to evaporate but could still suffer from water stress during the critical crop growth period (especially the terminal grain filling stage) which drastically affects the amount of the final grain yield. Excess water itself could also impose stress on rice growth at certain stages. Well-developed irrigation and drainage systems together with matching management practices can help maximize utilization of rainfall and river flows to achieve high yield and WP. Other land and crop interventions, such as laser land levelling, furrow-irrigated raised bed (FIRBS) cultivation, insects and diseases control, fertilizer and suitable variety, are also important factors to be considered along with water management.

Wheat ET, yield and water productivity indices are more consistent across the basin. High ET is accompanied with high yield and high WP. *Rabi* season is relatively dry thus the rainfall, stream and soil water availability is less significant. Irrigation becomes the main contributing factor of ET. Wheat yields are more related to irrigation volume. This explains the reason for high wheat yields in the Haryana, Indian Punjab and Pakistan Punjab: extensive irrigation is practiced in these areas, which is evidenced by a huge groundwater over exploitation zone in this area.

Both rice and wheat ET_a to ET_p ratio is higher in high rainfall areas. High rainfall means more water for evapo-transpiration. However, it does not necessarily lead to higher yield and water productivity, as shown from the yield maps and WP maps. This could be attributed to poor local crop and water management practices; especially the low fertilizer use, traditional varieties and incidence of crop diseases and pests. Rainfall may occur at anytime. Hence higher rainfall area has more water to evaporate but could still suffer from water stress during crop critical growth period (especially the terminal grain filling stage) which drastically affects the final grain yield accumulation. This is especially true for rice because rice yield and rice water stress (as indicated by ET_a/ET_p) showed contradictory trends. Wheat yield and WP follows more closely the trend of ET. As explained before, wheat relies heavily on irrigation due to the low rainfall. Hence high yield and WP is always accompanied with intensive input including water.

Further analysis revealed weather conditions as reflected by reference ET have no direct link with actual ET. The high elevation zones in the southern part of Ganges basin which is far from main river streams create problem for water access. However, large areas in flat plains and near to the main river streams also show very poor performance. The inconsistency between yield and WP distribution against the factors shows that while water availability is a major constraining factor in Indus basin downstream areas and southern part of Ganges, the main constraint in most of Ganges agricultural areas is not water availability or climate, *but the irrigation infrastructure, access to irrigation water and crop management practices*. Well developed irrigation and drainage system together with matching management practices can help to maximize utilization of rainfall and drain the excess water induced by intensive rainfall and shallow groundwater. Other land and crop interventions, e.g., land levelling, insects and diseases control, fertilizer, improved variety, are also important factors to be considered along with water management.

4.4.1 Scope for improvement of crop water productivity

Scope for improvement could be assessed in two steps: firstly through the comparison of “bright spots” and “hot spots”, secondly through site specific plant maximum photosynthesis capacity assessment. The second approach involves crop modelling for conjunctive water-fertilizer application and crop genetic innovations for high yield varieties. This is always the long term goals for the food security of the world. However, while agriculture in most developing countries is still at low level of management, the first approach provides greater chance for improved agriculture performance in near future.

The “bright spot” of both rice and wheat in Indian Punjab state and adjacent areas, with 5% of basin rice and wheat cropping area, has high WP of 0.190 US $\$/m^3$. If the basin average value of 0.131 US $\$/m^3$ could be increased to the same as in bright spots, the basin could theoretically save 31% of agricultural water consumption with same quantity of production or increase 31% of production with same quantum of water input. Although this is limited by many constraining factors, a reasonable increase in WP still has a lot of significance for regional food security.

The potential for rice and wheat is different both in terms of magnitude and areas of focus. Figure 4.10 shows the plots of water productivity to yield and yield to ET_a of rice. It could be observed that water productivity generally increases with increment of yield, with a relatively lower pace because ET_a too increases with yield. The “bright spot” of Indian Punjab is circled. The yield of this area is so high that it totally changed the slope of yield to ET_a (from S_3 to S_2). Some other areas also have similar ET_a, however, the yield is much lower. The scope for improvement of rice in the region will be to firstly target at the S_2 trend. That is, to improve the yield with similar water consumptions. In this process the water productivity could be expected to increase 15-25%. Final target would be to increase the yield levels of all areas to "bright spot" values, during the process of which even "bright spot" might improve, which could lead to another 10% improvement.

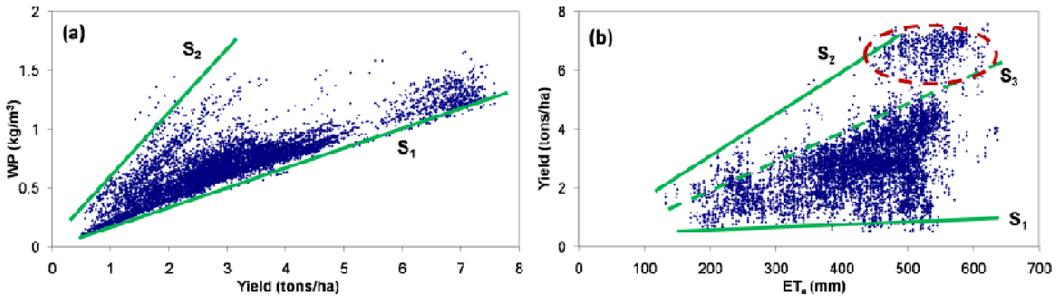


Figure 4.10. Relations between (a) water productivity and yield and (b) yield and evapo-transpiration of rice.

The above estimated potential for improvement is under optimal conditions, which assumes no irrigation water supply constraints, soil fertility could be improved to the same level as in Indian Punjab. And land and crop management practices could all be improved at the level of Punjab. However, some constraints, for example soil, are not easy to be ameliorated. Improving yield is a long term approach to improve WP and ensure sustainable development of the region. However, in the short term, reducing non-beneficial ET from low yield areas is a practical and convenient way of increasing WP and coping with water scarcity.

The levels of WP for rice and wheat in the basin are plotted in Figure 4.11. Large coefficient of variation (CV) values, 0.44 kg/m^3 for rice and 0.70 kg/m^3 for wheat, are found for both the crops. High CV means high variability in crop WP values, indicating significant differences in performance of crop water use. CV is reduced once basin performance is more uniform. In the Indo-Gangetic basin the CV of wheat is much higher than the CV of rice, meaning water management of wheat is more diverse compared with rice. This is because the rainfall during wheat growing season is very small, hence the irrigation contribution is more significant. Increasing the irrigation management levels for wheat is probably more urgent and easier to improve basin WP.

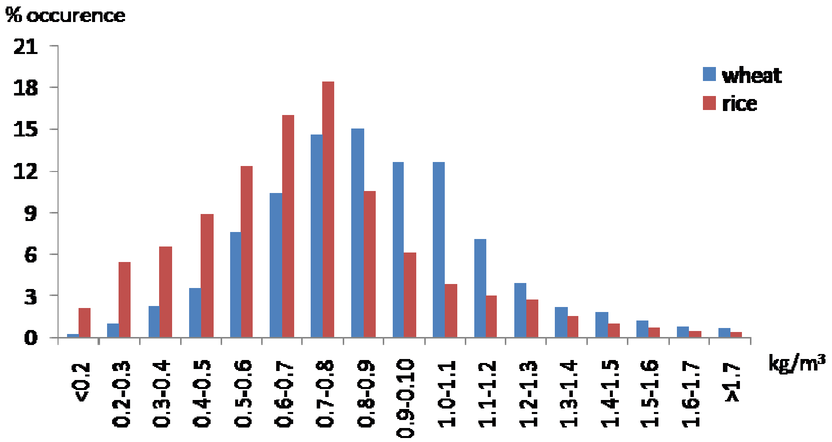


Figure 4.11. The histogram distribution of WP values for rice and wheat.

4.4. Fisheries Water Productivity in the Eastern Gangetic Basin

Inland fisheries form an integral part and provide livelihoods and food security to a large population in the eastern part of the Gangetic basin. Importance of fisheries for achieving high levels of water productivity is very high in Bangladesh, but is not very well understood. For better understanding of the relationship between water bodies and the fisheries and obtaining first estimates of fisheries productivity and water productivity, detailed studies were undertaken in the Gorai-Madumati sub-basin in the eastern Ganges basin in Bangladesh.

After an initial analysis of secondary data on production systems obtaining data as 'catch per unit area (CPUA)' and an understanding on spatio- temporal variation, the study looked at water productivity of different production systems by obtaining productivity of fisheries by weight and monetary values by volume of water in order to standardize the methodology with the water productivity of other crops. Results from the field on upstream to downstream variation for the different fisheries production systems and water productivity values in *production by volume* and *returns (Bangladesh Taka, BD Tk, 1USD~70 BD Tk) per volume* are also addressed.

4.5.1. Fisheries production systems

The most prevalent fisheries production systems include the following:

Capture fisheries systems: Capture fisheries cover a variety of habitat types: *beel, baor* and rivers. *Beels* are the low-lying depressions in the floodplain (small lakes) and may have a permanent character, containing water throughout the year (perennial *beels*) or dry out completely during a part of the year, usually 4-5 months (seasonal *beels*). *Baors* are specifically abandoned river courses; oxbow lakes. During monsoon the *beels* become part of the floodplain fishery which generates opportunities for subsistence fishing as 80% of rural households take part in fishing to contribute to the agricultural income and achieve the daily needs of household expenditure and/or protein supply. Rivers are large natural streams of water, with connecting canals that in some instances feed the *beels* with water.

Culture fisheries and integrated agriculture-aquaculture systems: In the eastern IGB, the fishermen adopt the following variants of culture fisheries

i. *Intensive aquaculture***:** The culture systems making good use of supplementary feed, and having high number of cycles per year and stocking density are referred as intensive aquaculture systems. These systems require good resources, technical knowledge and the market.
ii. *Semi-intensive:* Under semi-intensive systems fish fry is stocked only once annually and generally during the rainy season when there is sufficient stored water. Throughout the period from stocking to harvesting, only very small amount of feed (e.g. cooked rice, rice husks, etc.) is introduced, if any, and fish mainly depend on natural food supplements available within the system.
iii. *Extensive / low input aquaculture*: Extensive aquaculture requires less effort in fish husbandry. It is generally practiced in the manmade lakes, ponds, and closed or semi-enclosed water bodies. Fish selected for extensive aquaculture are very hardy and often low stocking densities are maintained. Carp, tilapia, pangus, and shrimp are the common species for extensive aquaculture.
iv. *Shrimp culture*: In the study areas of the eastern Gangetic Basin, especially in the southern areas which are closer to brackish waters, shrimp culture (both Galda and Bagda) either in mono or polyculture systems is widely practiced. The determinants that outweigh the scale for landowners to adopt aquaculture techniques are mainly water quality and quantity.
v. *Integrated agriculture-aquaculture system:* Integrated Agriculture- Aquaculture (IAA) system is a kind of culture where both land uses are mutually inclusive and support each other. In IAA systems, aquaculture is practiced in ponds with little or no water exchange. There are a number of farming systems, which can be regarded as variations on the IAA theme: (i) Farms based mainly on dryland crops and fish culture, sometimes with a small input from poultry or other livestock (ii) Wetland crops: rice and fish culture (iii) Integrated animal and fish farming e.g. pigs, ducks and poultry farmed together with fish.
vi. *Rice-fish*: Rice-fish culture is an integrated system that is mainly governed by availability of water. Cultivation of fish can be concurrent with rice crop or alternate with the crop cultivation. Rice-fish culture is preferred in large area due to its good profitability.

4.5.2. Water productivity for fisheries and aquaculture and its spatio-temporal variation

Fisheries water productivity has been obtained as catch per unit area (CPUA) from secondary data and calculated as volume of water using the data collected from the case study. The results for spatio-temporal variation of productivity throughout the sub-basin, and an account of productivity by volume in the three districts in the sub-basin are discussed below.

4.5.2.1. Beel system: All districts in the sub-basin showed a small decreasing trend for *beel* fish-productivity during 2002-2007(Figure 4.12). Even the high productivity regions (Rajbari, Madaripur and Gopalganj) showed some decline. Though Faridpur has smaller spatial variation, data shows that currently Faridpur remains a hotspot for *beel* productivity .*Beel* fisheries productivity in terms of CPUA has a clear peak in the northeastern part of the sub-basin, especially in Faridpur followed by Rajbari, Madaripur and Gopalganj. The least productive districts are located in the southeast, coinciding with the lower part of the sub-basin which shows a low and decreasing trend (Figure 4.13). The water bodies have low water-flow condition due to upstream water scarcity and delinking nature of the *beels*. High productivity in *beel* fisheries in the northeast is influenced by the Padma river flows (the Ganges and the Jamuna confluence). Connection with the Padma provides a good biological ground, as it facilitates migration, allowing hatchlings to enter the *beels*, it also provides good nursing grounds and adequate food. Proximity of the Padma ensures good water quality, and can cause water spillage, allowing the formation of perennial *beels* and year round production in the area. Seasonal water will increase the *beels* volume and create floodplains. Fisheries productivity in *beels* declines as one move away from the river streams.

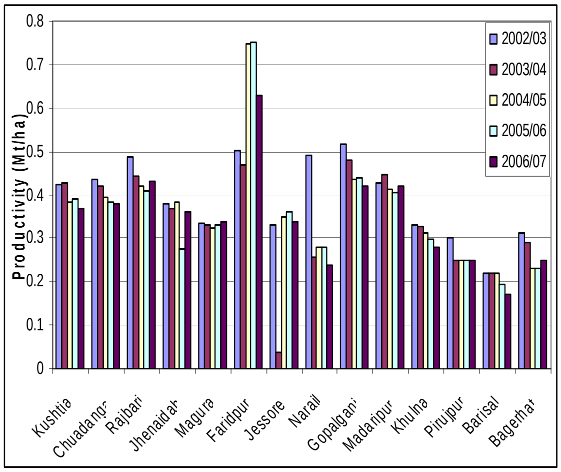


Figure 4.12. B*eel* fisheries (2002-07) productivity for 14 districts of Bangladeh. (Source: DoF, Bangladesh)

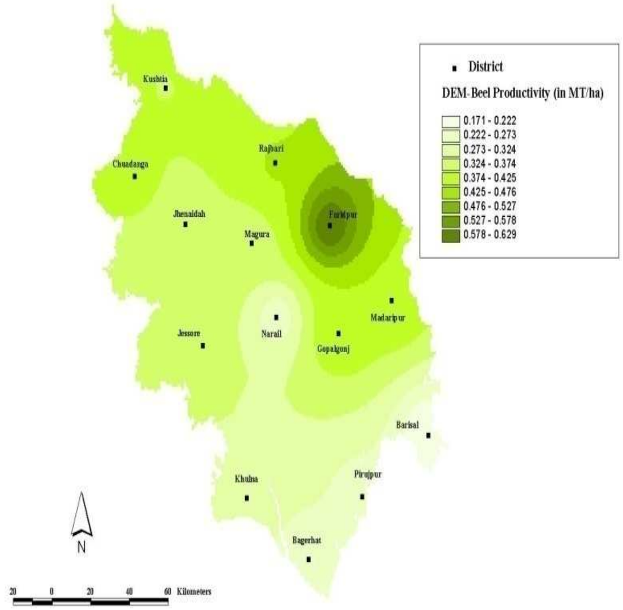


Figure 4.13. Spatial variation of *Beel* fisheries productivity in G-M sub-basin.

4.5.2.2. Baor (oxbow lake) ecosystem: The intensity of fish production in *baors* is higher in the northwestern region and gradually decreases towards the southeastern areas. The highest productivity is in Chuadanga district, followed by its neighboring district, Kushtia (Figure 4.14). The high *Baor productivity* hotspot in the north may be as a result of a good management system of the fishery in that area. The southernmost areas (Bagerhat, Pirujpur and Barisal) have no *baors* and hence are not comparable. The visible gradient reflects the pattern of *baor* concentration across the region where zones of higher presence of *baors* translate into a higher intensity of culture and better management.

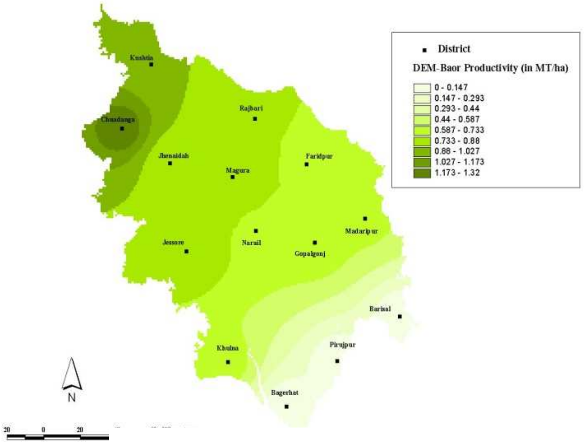


Figure 4.14. Spatial variation of *Baor* fisheries productivity in GM sub-basin.

Temporal data analysis of privately managed and government managed *baor*s has shown that (Figure 4.15) productivity of privately managed *baor* increased over time at a much higher rate than government managed *baors*. This data together with the Key Informant Interviews (KII) and expert judgment reveal a weakness in public management of *baors.* However, the overall productivity of *baors* remains low (<1t/ha) due to continuation of traditional practices with low yielding species, as compared to other countries, e.g. China and Vietnam which produce approximately 5 to 10 t/ha under similar agro-ecologies.

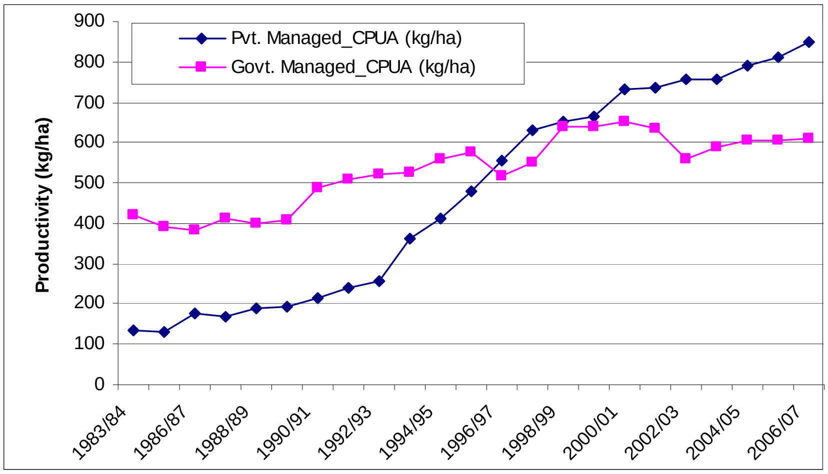


Figure 4.15. Temporal variation of *baor* productivity in the GM sub-basin.

4.5.2.3. River system: Production of river fisheries is highest in Barisal (28,839 tons), followed by Bagerhat, Pirojpur and Rajbari (Figure 4.16) districts. The remaining districts have poor production of river capture fisheries. The trends vary and show river *Mathavanga* upstream to have the highest fish productivity by weight and value (Table 4.4). This may be due to composition of fish species, the presence of high valued species, high biodiversity index and water flow upstream. Moving downstream we find a higher productivity (threefold) than midstream. The trend does not continue downstream in *KulirJorr* River, where fishers who usually catch fish also find *galda* and *bagda* shrimp. This is linked to a high biodiversity index, which is at the same time directly related to water availability and environmental flow conditions.

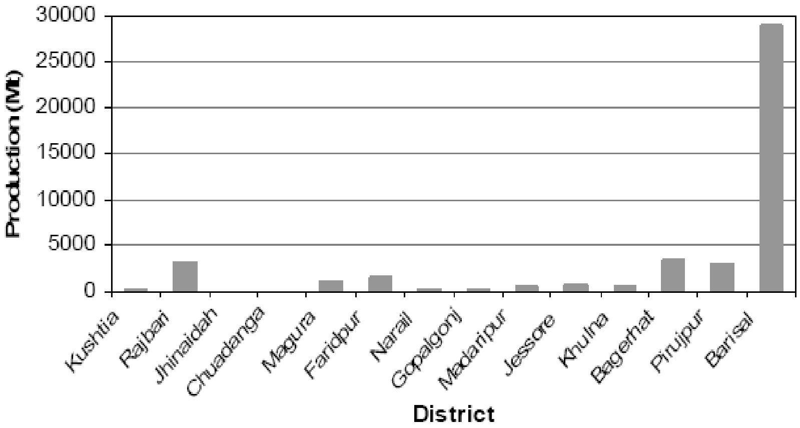


Figure 4.16. Variation in river fish production in the GM sub-basin, Bangladesh.

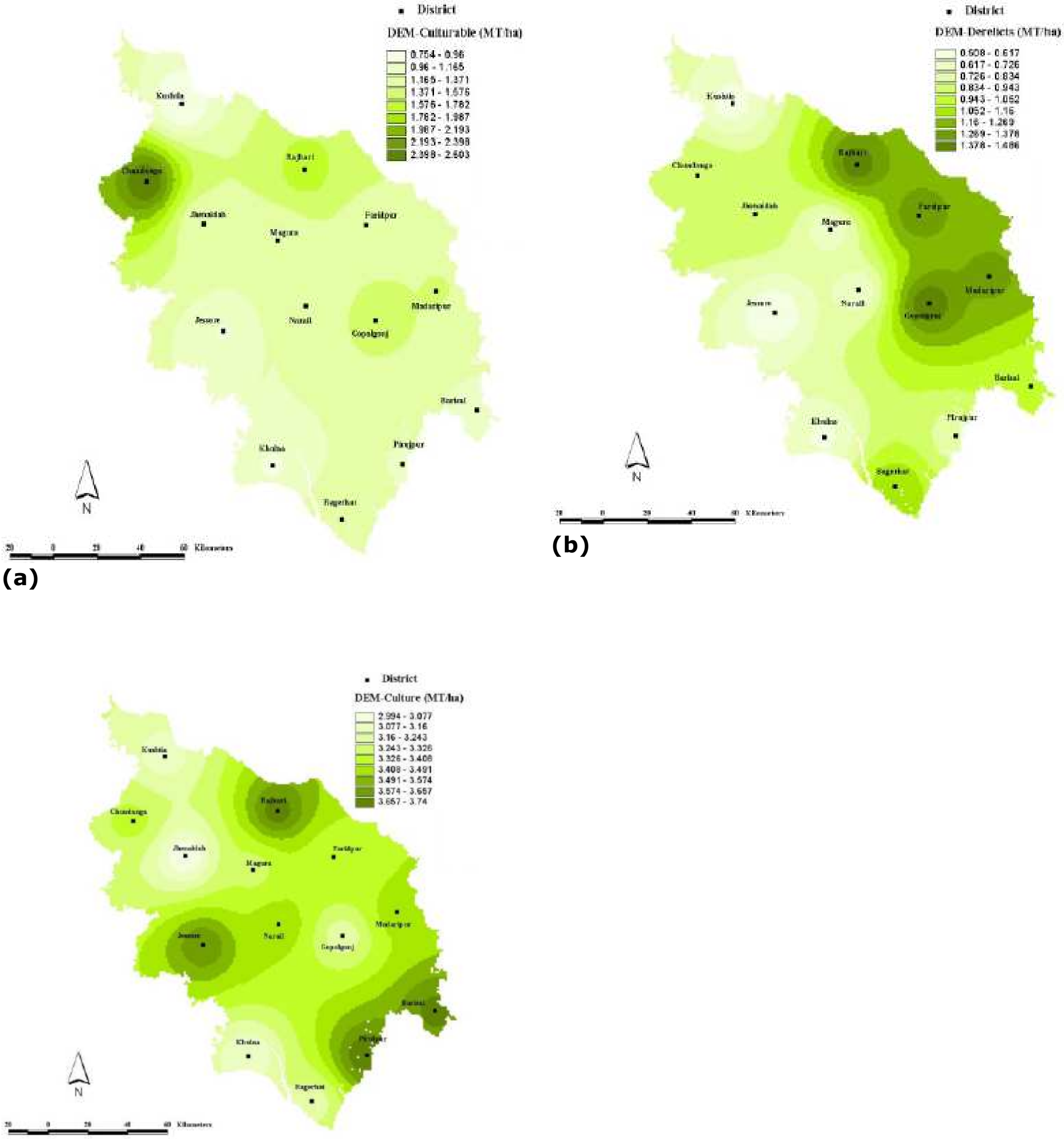
Table 4.4. River water fish productivity by weight and value of three river catchments in G-M sub-basin.

Districts	Name of the water body	Water productivity (kg/1000m^3)	Water productivity (BDT*/1000m^3)
Chuadanga	Mathavanga River	26.0	2,240
Narail	Nabaganga River	4.5	540
Bagerhat	Kulirjorr River	14.5	1,735

**BDT- Bangladesh Taka (1 USD~ 70 BDT)*

4.5.2.4. Culture fisheries and Integrated Agriculture- Aquaculture (IAA):

i. Freshwater pond habitats: Fish culture ponds have high fish productivity zones in the northwest, reflecting better management practices. South-west districts, especially Jessore and Khulna have low productivity of culture ponds (Figure 4.17(a), (b), (c). Derelict ponds adjacent to the rivers are notably more productive. The confluence of the tributaries of the main rivers in the northeast clearly coincides with the productive derelict areas, where river bank erosion may cause formation of the derelict ponds. In case of culture ponds, high productivity was observed in the north (Rajbari), west (Jessore) and northeast districts (Pirujpur and Barisal). These hotspots represent a range of productivity drivers. In Jessore, there are well established extension services and easy availability of seed from the hatcheries. The north is an advantageous ecological zone due to proximity of the productive Padma River, and the southern regions near the coastal belt take advantage of the salinity gradients to develop the profitable shrimp industry and extension of aquaculture practices.



(a)

(b)

(c)

Figure 4.17. Fish productivity elevation models (PEM) of (a) culturable ponds, (b) derelict ponds, and (c) culture ponds in the GM sub-basin, Bangladesh.

The temporal variation of aquaculture productivity (i.e. average of cultured, culturable and derelict ponds) for the fourteen districts shows Jessore and Khulna as most productive districts whereas Pirujpur, Gopalganj and Faridpur have lower fish productivity. Jessore district showed a slight decrease with time, whereas Khulna district showed an increasing trend of aquaculture productivity.

ii. Shrimp farm productivity: Traditionally established shrimp farming regions of Bagerhat and Khulna have shown a steady and high productivity while there is no visible trend in the other areas of the sub- basin. The neighbouring districts, especially Narail, Gopalganj and Jessore, also showed a steady productivity increase since 2002 (Table 4.5).

Table 4.5. Water productivity by weight and value of shrimp culture in selected ponds in three districts in G-M sub-basin, Bangladesh.

District	No. of ponds	*System type*	Productivity (kg/1000m^3)	Productivity (BD Tk/1000m^3)
Chuadanga	7	Intensive	323 ± 176	19,918 ± 13,967
Narail	1	Shrimp (*Bagda*) culture	68	34,136
	38	Shrimp (*Galda*) culture	41 ± 8	13,532 ± 10,601
Bagerhat	15	Shrimp (*Galda*) culture	22 ± 2.7	8,529 ± 6,072
	14	Shrimp (*Galda*) culture	19 ± 3.3	15,168 ± 8,095
	1	Nursery	50.10	10,025

iii.Integrated agriculture-aquaculture(IAA) system: Rice-fish systems (especially in Chuadanga) is the most productive integrated system having highest output both by weight and economic value. However, it is not a widespread culture system in the sub-basin (Table 4.6).

Table 4. 6. Water productivity by weight and value of some selected rice-fish and IAA systems in G-M sub-basin, Bangladesh.

District	No. of systems	System type	Productivity (kg/1000m^3)	Productivity (BD Tk/1000m^3)
Chuadanga	11	Rice-Fish	297±216	20,301±11,325
Narail	1	IAA (Fish product)	92	6,929
	7	Rice-Fish (Fish-product)	76±62	4,988±2876
Bagerhat	16	IAA	54±49	12,906±7684
	34	Rice-Fish	33±30	8,066±710

Based on the above findings, the brightspots identified for different fisheries system in Gorai-Madhumati sub-basin are as follows:

i. The north-eastern part of the GM sub-basin is the brightspot for *beel* system.
ii. The north-western side is suitable for high *baor* (ox-bow lake) productivity.
iii. The south-western side is specifically favorable for pond aquaculture and shrimp farming, and
iv. The coastal zone of the sub basin and its nearby districts has highest productivity for shrimp and prawn culture.

4.5.3. Factors affecting fisheries productivity

Factors affecting variation in fisheries productivity as identified by the primary survey include scarcity of water and poor access to water resources, suitability of the pond for fish culture (i.e. area and cleanliness), quality of the fingerlings, proneness of fish to diseases, and the high fish feed price and lack of training (Table 4.7). Downstream in the sub-basin, issues of high temperature and salinity ingress were also raised.

Table 4.7. Main constraints for improved fish culture in the study districts in GM basin, Bangladesh.

District	Constraints for fish culture
Chuadanga	Scarcity of water
Narail	High price of fish meal Scarcity of quality fingerlings Proneness to fish diseases Lack of suitable training
Bagerhat	Increase in salinity levels Increase in temperature

(Source: Primary survey by the authors)

i. *Capture fisheries*: Changes in land use have decreased the availability of water and hence the productivity of water bodies. Indiscriminate agricultural intensification programs do not appropriately assess their impact on fisheries and also cause environmental degradation. Industrial waste disposal and agro-chemical pollution of water is another factor degrading the quality of water and reducing productivity. Lack of infrastructure and transportation facilities also pose a serious hindrance to the marketing. There is a lack of adoption of good practices and sustainable management measures at large and illegal and destructive fishing and overfishing in non-leased areas of open water system, particularly in the rivers, tributaries and floodplains – reducing the availability of produce and the sustainability of fisheries. This lack of management, coupled with lack of coordination and insufficient capital act as constraints to achieve potential productivity. Present leasing systems of water bodies lead to a tragedy of the commons, indirectly encouraging the exploitation of resources leading to destructive fishing methods, dewatering of water bodies and other environment- threatening fishing practices.

ii. *Closed and semi-closed culture fisheries:* Poor marketing system, infrastructure and transportation facilities affect culture fisheries as they do capture fisheries. Adoption of environment- friendly and sustainable technologies for fish stock conservation is not addressed in the national policies and is further constrained by poor availability of quality seed and feed product, fertilizers and other fish culture materials. The inheritance of ponds cause multi-ownership of water bodies, and this leads to conflicts between the owners. Again, leasing policies are outdated and government/ public ponds do not offer equal opportunities for fishermen.

iii. *Shrimp farming and coastal aquaculture:* Shrimp productivity is affected by insufficient capital, lack of coordination and management instruments among the fishers, poor infrastructure and transportation facilities, and weak market linkages. Shrimp farming will be more productive with saline water but agricultural crops are hampered by salinity. There is a lack of proper land zoning –although policy for it is being drafted and in some cases shrimp farmers will take advantage of this black hole to settle their saline ponds in the area of their choice.

4.5.4. Threats to fisheries productivity in the eastern Gangetic basin

Fisheries productivity in eastern Gangetic basin is threatened by various factors, some of which are detailed below:

i. *Water resource development interventions*

Water resources development projects, planned with less sensitivity, were found to be detrimental to open water fisheries. For example, flood control and drainage and/ or irrigation (FCD/I) interventions have caused a reduction of water area and volume (floodplain area reduced from 9.3 M ha to 2.8M ha over the last four decades), hampered the migration and spawning of aquatic organisms, increased siltation of *beel* beds and thus reduced/ eliminated the overwintering shelters. These project interventions have also caused delinking of the rivers and *beels* . Further draining of *beels* for irrigation purposes and contamination with agro-chemicals significantly reduced their fish productivity. Most of the interventions of the water sector were favorable for paddy cultivation as most planners tend to value fish as less important for national food security. Dewatering of *beels* is also one of the water resource development interventions, which can create disastrous and critical ecological conditions and rapid siltation can raise *beel* beds and alter and disrupt the connectivity of the *beels* with the rivers and floodplains. Negative impacts of these development projects are shown in Figure 4.18 where the changes in land use substantially reduced the open water fisheries productivity. Feeding and breeding habitat and migratory routes for small and large native species of fish are also disrupted and the conversion of land use from fisheries to agriculture lead to intensification of agriculture practices (HYV) which are likely to increase the use of agrochemicals and pesticides posing a potential threat to local fish stocks.

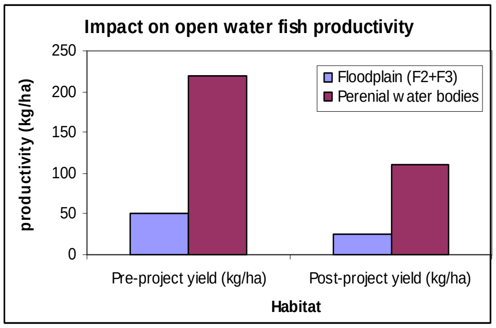


Figure 4.18. Impact of water resource development projects on open water fish productivity in the GM sub-basin, Bangladesh.

ii. Climate and land use change

As per the farmers' perception and climatic data, the droughts have become more severe and frequent. Fishers of Narail district reported a drought that has prolonged from mid-March to mid-June. In case of Bagerhat, fishers and fish farmer's responses agreed on length of drought and its severity. According to them, drought (no rain period) generally starts from Mid-February to Mid-April. But for the last several years it has prolonged for one more month. Salinity in water is also increasing. It is observed mainly in Bagerhat and Narail. Being situated adjacent to the coast, inhabitants described salinity during dry season as intolerable. Reports claim that sea level is rising at the rate of 5mm/year over the last 30 years. Professional observations and farmer perceptions suggest that in the near future the present economic activities may become un-suitable and the community will need to change the land use practices. This needs to be rigorously assessed and projected along with the development of suitable adaptation measures. Brackish water fisheries and marine culture may offer opportunities for alternative measures for sustaining livelihoods of the vulnerable fisher communities.

iii. Changes in environmental flows

Water flow in river measured in terms of water depth has been declining during the last decades (*refer* water balance analysis of the Gorai river catchment in Chapter 3) due to higher uses upstream and the situation tends to become worse during the dry season. In case of Chuadanga, farmers reported a minimum depth of water in most *beels* including *Raisar Beel*. This caused detrimental effect on the life cycle of some aquatic species, particularly in the overwintering shelter of the spawning fish stock. These species undertake spawning migration in the pre-monsoon but the route of migration is obstructed resulting in lower spawning efficiency. This leads to lower natural fisheries regeneration capacity and hence can lead to overfishing as the fish stock will be reduced and the fishers will be easily catching these from a smaller volume of water.

iv. Access to water bodies

Access to open water bodies is provided on the basis of prevailing leasing policy and other project based interventions. Participants reported that they are well aware of prevailing leasing policy/practice of open water bodies in the area. Traditionally, open water bodies were leased to the poor fishers through project-based initiatives. But recently this method is not followed by the concerned department. Poor fisher don't have leasing right to open water bodies. The recent revision of the Waterbody (Wetland) Leasing Policy has added another dimension to the effect that the law makers of the respective constituencies would advice on the fishers' groups to get the leasing right and that is viewed as opening a window for restricted access of the real fishers in the water bodies. This needs to be reviewed and made pro-poor. Another problem is that currently some influential people in the localities have enlisted themselves as fishers though they are not actually fisher by profession. As a matter of fact, with this fraudulent activity supported by the political influence, they have been managing to grab the entitlement of leasing rights.

4.5.5. Improvement of fisheries water productivity

The study revealed that there exist a large scope for the improvement of fisheries water productivity in the eastern Gangetic basin. The priority options included the following:

i. For intensified pond culture and shrimp farming, use of quality seeds was identified as a key pre-requisite for optimizing aquaculture productivity.
ii. Decentralized fish seed production and marketing system was identified as a good tool for harnessing the aquaculture potential given the variability in water access and availability.
iii. Culture cycle rotation, especially rice-fish cultivation, is a potential future intervention.
iv. In case of rice-fish, depending on availability of land and water there could be alternate rice and fish, and at times simultaneous culture. For shrimp production, it would involve cycles of shrimp growth alternating with culture of other fish species.
v. Rice-fish offers the possibility of water storage in trenches for supplementary irrigation at critical cultivation points for rain fed rice.
vi. Community based resource management, community based *beel* and *baor* management, habitat restoration, natural stocking for recruitment and sanctuary establishment are all potential management practices for ensuring and improving capture fisheries productivity.
vii. Quality fish-seed, nursery and decentralized seed farming technology and improved marketing dynamics can ensure and improve water productivity of pond aquaculture.
viii. Cage culture, seaweed and mussel culture in the coastal region present an opportunity for improving coastal water productivity.

4.6. Sustainable Rural Development through Improved Water Productivity

Water is one of the key natural resources in supporting livelihood of rural population. The Indo-Gangetic is a highly populated basin with more than 70% of the people living in rural areas. The social and economic development in large part of the basin is at fast pace. However, the development in rural areas varies from location to location and farmer to farmer and for large number of poor and marginal farmers' availability and access to an assured water source is the first step to move up the value chain. Water has to produce more outputs and deliver more services to support the rural development. That is, to sustain rural development through improved water productivity.

Crop water productivity improvement is a fundamental requirement for sustainable development. The Indo-Gangetic basin is experiencing various degrees of water scarcity. The Indus is already a physical water scarcity region and the Ganges is under growing pressure. The agricultural water sector is seen to get less water allocation in the future in spite of the growing food demand. WP gains have to be achieved to enable farmers to cope with the challenges. These WP gains are required for every part of the basin including "bright spots" and "hot spots". The upstream of Indus basin, where the highest crop WP is found, has serious problem because of groundwater over exploitation for irrigation. The groundwater table in these areas has decreased dramatically during the last decade and is still decreasing. This situation makes the agricultural development unsustainable, which threatens sustainable development of the area. Irrigation withdrawal has to be optimized to a certain level that the local ecosystem be sustained and also crop production targets adequately met. In the Gangetic basin, low water productivity is mainly associated with economic water scarcity with farmers having limited access to the available resources either due to high energy (diesel) prices and/or poorly functioning canal irrigation systems. This area can witness a large turn-around with properly targeted investments and policies.

Livestock and fishery are central to enhance income of rural communities hence reduce the vulnerability to risks. In eastern IGB, particularly in Bangladesh, fisheries play an important role in nutrition, employment and rural economy. It is the only sector that provides opportunities for open access livelihoods for the rural poor and ultra-poor of eastern IGB. Initiatives which improve integrated enterprise development of the aquaculture value chain, from enhancing seed quality and distribution through marketing aquatic products, can help increase incomes and improve livelihoods for fishers and fish-farmers. Interventions to increase the water flow and flushing conditions of the aquatic ecosystems are found to be a win –win situation for achieving an increase in fisheries productivity and have a beneficial impact on the society including the agricultural farmers. Leasing policies for the open water bodies need to be made transparent and pro-poor with encouragement to women and community based institutions.

Sustainable rural development also requires full function of water services including the whole of ecosystem, hydropower, household uses, etc. Agricultural water productivity is undoubtedly the most important element in rural sustainable development. However, other water services and outputs are important components to be considered at the basin level integrated water management. Ecosystem delivers wide range of services to support human survival and development. Water management, for example, pollution control, and optimal environmental flow, is the key to a healthy ecosystem. Hydropower is another significant output from water. However, in many cases hydropower is competitive user which may lead to reduced irrigation water allocation and consequently reduced agricultural production. Good hydropower management optimizes water allocation and support the energy demand of rural areas.

4.7. Conclusions

Basin water productivity assessment is of huge significance for better regional water and land management. Proper understanding on the magnitude of WP, the variations, and the scope for improvement is essential in achieving sustainable development to ensure food security.
Multiple agricultural water uses exist in the Indo-Gangetic basin which leads to diverse agricultural outputs. Overall agricultural WP in the basin is not low with significant contribution from livestock and fisheries. However, significant scope exists to improve crop water productivity in large regions.

Rice and wheat water use and water productivity are relatively low with tremendous variation in Indo-Gangetic river basin, which indicates significant scope for improvement. Comparative analysis on yield, actual ET, potential ET with temperature, rainfall distribution, topography, groundwater depth, and distance to main river streams revealed some interesting clues to study causes for variation. It is discovered while rainfall provides vital inputs to agriculture, excess water could also lead to low yield and high non-beneficial ET. Climate conditions, topography and agriculture distribution has less significant impact on crops within the basin. The successful “bright spots” suggest appropriate irrigation and drainage infrastructure and matching management practices are the key to sustain high performance.

Scope for improvement could be assessed from the “bright spots” in comparison to “hot spots”. The bright spot in Indian Punjab State and adjacent areas, with very high WP, is the “model” for other areas. If the basin average value could be increased to the same as in bright spots, the basin could theoretically save 31% of agricultural water consumption with same quantity of production or increase 31% of production with same quantum of water input. Although this is limited by many constraining factors, a small increase in WP still has a lot of significance for regional food security.
Overall, the findings of this research could be concluded as:

i. The productivity of land and water as generated from rice and wheat as well as sugarcane, pulses, and millet etc, is crucial to the livelihoods of the huge rural population in the basin.
ii. Basin average yields and water productivity of the predominant crops (rice, wheat) are generally low despite intensive agricultural activities.
iii. Huge variations exist across scales from farm to the basin. An overall declination from northwest to southeast is observed. In contrast to the bright spots of well performing areas, for example, Indian Punjab and Haryana (only about 7% of the basin area), large areas come with extremely poor performance (Bihar, Bangladesh…).
iv. The variability shows no direct relationship with climate conditions and topography, implying the significance of well regulated irrigation and associated crop and water management.
v. Significant scope exists for improvement, which could be achieved mainly by long term yield enhancement. In short term, reducing non-beneficial ET of low yield areas can also largely contribute to improved water productivity.
vi. Both capture and culture fisheries and the intensive agriculture-aquaculture systems offer great scope for improvement of water productivity and livelihoods of the poor fishermen in the water congested areas of the eastern IG basin. With proper seeding, feeding, management, institutional credit and marketing and pro-poor leasing policies of the open water bodies, the fisheries and aquaculture can potentially transform the rural economies of the poor and vulnerable households.

5. AGRARIAN CHANGE AND WATER INSTITUTIONS IN THE INDO-GANGETIC BASIN

Tushaar Shah, Aditi Mukherji, Sanjiv de Silva, Dhruba Pant, R.P.S. Malik, S. Hervas, M.G. Khan

5.1. Role of Agrarian and Water Institutions in the Indo-Gangetic Basin

Water sector, during the last few decades, has to a large extent been successful in developing technical solutions to meet the growing water requirements of the different sectors of the economy and different sections of the society. The success of these interventions however relegated to the background the need for and significance of an appropriate governance structure to facilitate management and more efficiently use the water resources so developed. With the development of additional water resources becoming more and more difficult and expensive coupled with continued rising demand for water from all sectors and increasing conflicts at all levels on sharing of available water has brought in to fore the consequences of ignoring water sector governance. With the increase in conflicts of water sharing, the acceptable governance mechanisms become all the more complex when the resources are of transboundary nature as the Indus and the Ganges rivers. It is now being increasingly believed that the so-called 'water crisis' is essentially a crisis of governance. There is now a growing appreciation that increasing the focus of attention and depth of future efforts on governance of the sector- in all its dimensions- is crucial for its sustenance. The concern for and importance of effective water governance has been emphasized, amongst others, by the Global Water Partnership (GWP) in a concrete and sound way describing it as a tool to provide water security for the development of humanity. However, despite becoming a popular and widely used term in the last about one decade or so, there is still neither an accepted definition/ framework of water governance and consequently nor on how good governance in the water sector can be accomplished.

The subject of governance has been a theme of substantial research and many researchers have attempted to analyse institutions and institutional changes in the water sector from different perspectives. The theoretical literature elaborating the gains possible from institutional changes – both in the general and in the water sector contexts – is vast and growing. The concern on institutional analysis in most of these analyses has generally focussed on water law, water policy and water administration- often referred to as the three pillars of institutional analysis. However, if institutional change is about how societies adapt to new demands, its study needs to go beyond what government bureaucracies, international agencies and legal/regulatory systems do; people, businesses, civil society institutions, religions and social movements – all these must be covered in the ambit of institutional analysis.

Indo-Gangetic Basin (IGB) water sector exhibits a large variety of such informal institutional arrangements, which co-exist with large formal institutions (Saleth, 1996). Much information is however not known about the extent, nature and intensity of involvement of formal and informal institutions within different regions in IGB as also within a given region over different tiers of resource management. There is also a lack of clear understanding on the complex inter-relationships between the formal and informal institutions, their relative strengths, weaknesses and efficacy under varying resource availability, economic, political and other underlying conditions. What role the institutions have been making and in what ways these can potentially impact in promoting sustainable use of resources, contribution to pro-poor growth and economic development. Little information is available on what has been the process of institutional change in the IGB and what has been the nature and direction of these changes (Saleth and Dinar, 2004). The lack of an analytical framework to investigate and answer some of these questions has hindered comprehensive analysis of issues related to water governance in the region. This chapter is not a comprehensive review of all these issues of water governance but presents a brief account of some of the more pressing issues studied under the Basin Focal Project for the Indo-Gangetic Basin (BFP-IGB).

5.2. Is Irrigation Water Really Free in the IGB?

"Getting prices right" is the silver bullet widely advocated to developing countries in fighting waste, misallocation and scarcity of water. But this has begun to conjure up altogether different images in the IGB than in the global water discourse. When the use cost of water rises above the low threshold, millions of small farmers here respond to rising irrigation prices initially by improving water use efficiency, by investing in lined channels or pipes for conveying water, and by switching to water-saving crops. However, when water use cost rises beyond some upper threshold, farmers are increasingly forced, in distress, to respond by drastically curtailing irrigation water use or even by exiting irrigated agriculture or agriculture itself. High water use cost achieves water use efficiency but threatens livelihoods and food security of millions of agrarian poor. Such stress is evident throughout the IGB (Shah et al, 2009).

As a consequence of shrinking public irrigation and rapidly growing private irrigation, the fast changing profile of South Asian irrigation economy was somewhat like what is shown in Figure 5.1 during early years of the new millennium. The lowest range of water use costs (ranging from US $ 0.0025 to 0.02/m^3) is for flow irrigation from canals and tanks that partially supply, at most, 30–32 Mha; the highest (at US $ 0.15–0.25/m^3) is paid by farmers at the other extreme, hiring diesel generator sets to generate electricity to drive submersible pumps on deep tubewells. Naturally, this last option is used in extremis on very small areas for a life-saving irrigation or two. The point remains that the highest irrigation water cost/m^3 of water applied incurred in South Asia can be as much as 100 times the lowest, that more land is under irrigation at non-trivial use cost, and that the productive value of water at the margin must exceed the use cost for such expensive irrigation to continue.

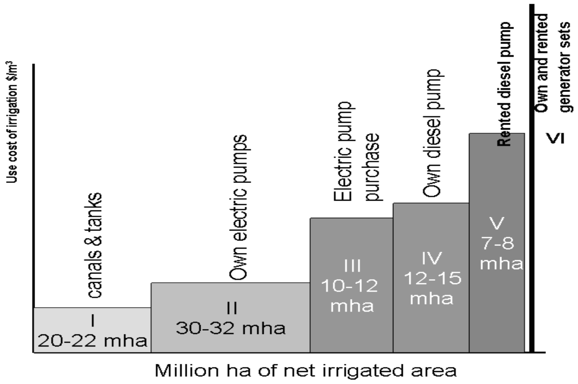


Figure 5.1. Irrigation sub-economies of South Asia. (Source: Shah et al. (2009).

The global "water pricing" debate, applies partially only to the first—consisting of canal and tank irrigated areas—out of South Asia's six irrigation sub-economies; here, water use cost borne by farmers is neither volumetric nor anywhere near the "threshold." In all the rest, energy costs dominate the actual use costs of irrigation water. In sub-economy II, comprising areas irrigated by electrified tube-wells, the use cost of water is dominated by electricity costs which are high (at US c 1–1.75/kW h) and volumetric in Pakistan, Punjab, Sindh, Nepal, and Bangladesh. In India, electric tubewell owners are subject to flat tariff, but increasingly, these have to contend with stringent rationing of increasingly unreliable power supply. For farmers in sub-economies II, III, IV, V, and VI, irrigation water is very much an economic good; and the user cost facing them is well above the "threshold" beyond which irrigation water demand becomes price elastic. Even within sub-economies I and II, increasingly, farmers are resorting to the use of diesel pumps to cope with the unreliability of surface irrigation as well as electricity supplies.

5.2.1. The diesel price squeeze

The groundwater economy of the IGB (especially the Ganges) is dominated by diesel pumps, which impose a high volumetric water user cost on the basin's farmers. Barring Indian Punjab and Haryana, which have sizeable numbers of electrified tubewells, the rest of the IGB (Pakistan Punjab and Sind, Bangladesh, Nepal *terai*) overwhelmingly depends upon diesel pumps for irrigation. Electric pumps are insignificant because electricity supply to farms is metered and expensive as in Bangladesh and Pakistan or is simply not available (as in Bihar, and Nepal *terai*). The water use cost paid by a large majority of irrigators in irrigation sub-economies II, III, IV, V, and VI in the IGB is not only well above the "threshold" but is also approaching levels where it is beginning to squeeze out smallholder irrigation itself. Since 2000, all available evidence suggests that the region's groundwater economy has begun shrinking in response to a growing energy squeeze. This energy squeeze is a combined outcome of three factors: (a) progressive reduction in the quantity and quality of power supplied by power utilities to agriculture as a means to contain farm power subsidies; (b) growing difficulty and rising capital cost of acquiring new electricity connections for tubewells; and (c) a 6.7-fold increase in the nominal price of diesel during 1990–2006, a period during which the wholesale price index for all commodities for India a little over doubled, but more relevant, the nominal farm gate rice price rose by just over 60%.

Since 2002, diesel prices have jumped over 70%; no surprise then that the diesel price squeeze on small-scale irrigation is heading towards a crisis in all the countries of South Asia but is particularly visible in eastern India and Nepal terai where the ratio of rice to diesel price has turned particularly adverse as evident in Table 5.1. Smallholders in Pakistan and Bangladesh enjoy some respite thanks to higher subsidy they enjoy in diesel prices. The fact remains that high marginal cost of irrigation with diesel pumps will keep irrigation water demand price elastic and stimulate IGB's smallholders to economize on water use in various ways.

Table 5.1. Farm gate price relative to diesel price in IGB countries.

	Diesel price per liter: February 2007	Farm gate rice price per kilogram: February 2007	kg of rice needed to buy a liter of diesel
India (Indian Rs.)	34.0 (US c 85)	6.4	5.7
Pakistan (Pak. Rs.)	37.8 (US c 64)	11.8	3.2
Bangladesh (Taka)	35.0 (US c 50)	9.0	3.9
Nepal terai (Nepal Rs.)	57.0 (US c 84)	10.0	5.7

Source: From various village studies undertaken for this research.

5.2.2. Energy squeeze leveraged through water markets

Because decentralized, fragmented water markets are natural oligopolies (Shah, 1993), pump owners use diesel price increases to raise their pump rental rates in tandem with every major rise in diesel price despite the fact that pumps themselves have become cheaper in real terms during 1990–2007. Electric tubewells, subject to flat horsepower linked tariff, are cheaper to operate than diesel pumps; their owners also sell pump irrigation to marginal farmers and sharecroppers at lower rates compared to diesel pump owners. Therefore, new electricity connections are avidly sought after. However, most IGB states—which in the early 1960s gave district collectors monthly targets for minimum number of tubewells to be electrified–now operate an embargo on new electricity connections to tubewells; and where they are issued, the entire cost of taking the power line to the tubewell— of poles, cables and transformers—is charged on the farmer. This has made new electricity connections scarce as well as prohibitively costly. Even so, existing electric tubewell owners and marginal farmers who are close enough to their tubewells to buy pump irrigation from them are luckier compared to diesel pump owners and their buyers. Since farmers who can buy pump irrigation from electric tubewell owners incur lower cost than by using their own diesel pumps, diesel pump owners in Uttar Pradesh today prefer purchased irrigation from electric tubewells than by irrigating with own diesel pump.

5.2.3. Shrinking water markets

The energy squeeze has raised the use cost of pump irrigation water and thus imposed a ''surrogate water price'' on farmers that is well beyond the ''threshold'' to a level that is proving immiserizing for marginal farmers and share croppers. Most social impacts of the energy squeeze on smallholder irrigation—and the agrarian poor—work out through groundwater markets. Confronted with the energy squeeze, these are shrinking; and soaring water prices are driving out water buyers and diesel pump irrigators who abound in the IGB. The key result is the shrinking of water markets. Some of the poorest farmers in the IGB are paying Rs. 2.11–2.67 (US c 5–7)/m^3 of irrigating crops. At such prices, irrigation cost would amount to a third or more of the value of crop output. In eastern India, Nepal terai and Bangladesh, electric tubewells are few and far between. Where we find some, two impacts follow: first, their owners find their monopoly power enhanced, which they use to increase their share in groundwater markets and irrigation surplus; second, they are able to moderate the energy squeeze on marginal farmers especially when power supply situation is good and tubewell owners pay flat electricity tariff. We found this to be the case in Uttar Pradesh, West Bengal and Orissa in India.

5.2.4. Response of water demand to soaring use cost

Soaring diesel prices and shrinking farm power supply are forming a pincer that first began forcing IGB's small-holder irrigators to make myriad adaptations to increase the efficiency of energy use in pump irrigation; some of these involved reducing pumping cost/m^3 either by switching to fuel efficient Chinese diesel pumps, or by switching from diesel to kerosene, and where possible, to electric power. A good deal also involved reducing water withdrawals. But more recently, the energy-squeeze is gradually driving smallholders out of irrigation, and increasingly, from farming itself.

Our case studies of 19 villages in Indian and Pakistan portions of the IGB do suggest two classes of responses, which we may call efficiency responses and distress responses. In the first category come all the adaptations made by smallholders to retain their irrigated agriculture by reducing somehow their groundwater use costs. These include attempts to curtail water use per acre by improving distribution efficiency (through lining field channels or using flexible pipes to convey water from wellhead to plants), by resorting to just in time irrigation and reducing the frequency of watering, by switching to low water demanding crops and crop varieties. In India as well as Pakistan, soaring diesel prices have rapidly increased the demand for electricity connections; however, these are getting increasingly difficult and costly to get because government power utilities now expect farmers to pay for cables, poles, and the transformer—all of which may double or even triple the cost of electric tubewells. In eastern India, therefore, besides reducing number of irrigations and area under irrigation-intensive *boro* (pre-summer) rice, a common response was to switch from Indian to Chinese diesel pumps, which are cheaper. Farmers preferred these for their low price, their much higher fuel efficiency (0.35–0.4 l/h), and most importantly, their ability to work on kerosene, which is cheaper than diesel due to government subsidy for cooking fuel. Distress responses sometimes included forced exit from farming all together. In eastern parts, those quitting farming were mostly marginal farmers and sharecroppers dependent on expensive purchased irrigation service from water sellers. As we move west, rising groundwater use cost has hastened the exit of medium-scale farmers many of whom had already invested in off-farm livelihoods. These typically leave their farms in the hands of migrant sharecroppers who now take the brunt of the energy cost squeeze. Another distress response of smallholders is switching to high-risk–high-value crops on a small plot of land while leaving the rest of the farm holding fallow or under rain-fed crop. That the choice of high-value–high-risk crops was more common among marginal farmers and share croppers dependent on purchased irrigation than among medium farmers with own tubewells was an indication that high groundwater use cost was the driver of this ‘‘gambler’s choice.’’

5.3. Energy-Irrigation Nexus in IGB

One of the most significant developments in South Asia in the last five decades has been the quiet ascendancy of groundwater as the main source of irrigation. Indeed Green Revolution has often been described as a tubewell revolution (Repetto, 1994). But it came at a cost. While the groundwater economy of India boomed, it did so at the cost of the India’s energy economy. This is because since the late 1970s, all state electricity boards (SEBs) in India decided to shift from metered electricity tariff to flat rate tariff system for administrative ease. While the original idea was to keep raising the flat tariff to reflect costs of generation and distribution, in reality, these tariff remained downwardly sticky and were used as populist electoral tools. Soon, the gap between cost of supply and revenue earned increased and most SEBs started making huge losses. With the liberalisation of the Indian economy in 1991, the losses of the SEBs became a matter of concern and there were calls from the donor agencies and national policy makers to undertake power sector reforms. Accordingly, the government of India (GOI) passed the Electricity Act, 2003 and power sector reform process picked up pace.

There were equally serious implications for the groundwater sector. Since the marginal cost of extracting groundwater was close to zero, it provided incentive for over-pumping. In many areas this spawned active groundwater markets. These markets emerged in response to unmet demand for irrigation and the flat tariff system. However, in arid and semi-arid regions with hard rock aquifers, flat tariff was directly responsible for over-pumping and, given the low recharge potential of these aquifers, water tables declined sharply. This in turn put in jeopardy the livelihoods of millions of poor farmers dependent on groundwater irrigation (Moench, 2007). In contrast, in areas of abundant rainfall and rich alluvial aquifers with adequate recharge during the monsoon season (example West Bengal, Mukherji 2007a and 2007b); the flat tariff system did not induce over-exploitation of groundwater.

Thus, there are not one, but two “energy-irrigation” stories in South Asia. The one that is often told is that of vicious cycle of low flat tariff, leading to over-exploitation of groundwater resources and bankruptcy of electricity boards, but which cannot be broken due to strong entrenched interests of the farmers. This is true for north-western states (Punjab, Haryana, and western UP) of the basin. The other part of the story, and often untold, is that of water abundant eastern India, Nepal terai and Bangladesh where most of the pumps are run on diesel and there is a severe energy squeeze. It is here that energy-irrigation nexus plays out differently. The work that we undertook in this work package of the IGB-BFP studied the energy-irrigation nexus in both the set ups. The following sections summarize our work on Energy-Irrigation nexus in India.

5.3.1. Electricity policy and groundwater use: evidence from Gujarat, West Bengal and Uttarakhand

Given both water resources and electricity are state subjects in India, individual states have chosen to go about differently vis-à-vis power sector reforms keeping in mind the political exigencies faced by these states. The states of West Bengal in the east and Uttarakhand in the north have embarked upon the path of universal metering of agricultural electricity consumers mainly because there are no strong farm lobbies in the state to oppose such a move. This shift from flat rate tariff (signifying zero marginal cost of pumping) to pro-rata tariff, altered the cost and incentive structure of the pump owners and hence affected their pumping behavior. On the other hand, the government of Gujarat, in face of strident farmers' opposition, decided not to meter tubewells, but instead separated agricultural feeders from non agricultural ones, improved the quality of power supply and rationed the number of hours of electricity to agriculture for only 8 hours in a day, thereby influencing farmers pumping behavior. This initiative of the government of Gujarat is called the *Jyotirgram Yojana*.

In this section, we will document the electricity reforms undertaken by different states and present a first cut analysis of the impact of these reforms on the pumping behavior of pump owners, on the informal groundwater markets through which water buyers would be impacted and on the revenues of the state electricity boards.

5.3.1.1. Groundwater and electricity situation in West Bengal, Uttarakhand and Gujarat

West Bengal, an eastern state of India has a groundwater potential of 31 billion cubic meters (BCM), most of which is available at shallow depths. Only 42% of the total available groundwater resources in the state has been utilized so far (WIDD, 2004). While West Bengal has plentiful groundwater resources that can be further developed, the state have for various political reasons (Mukherji, 2006) adopted one of the most stringent groundwater regulations in India. For instance, procuring electricity connection for tubewells needs permission from multiples sources, such as the State Water Investigation Directorate (SWID), village level bodies (*panchayats*) and the process is fraught with red-tape and corruption. The result is that West Bengal has the lowest proportion of electric tubewells to total tubewells in India (GOI, 2003). The farmers in West Bengal, till 2007, also paid the highest flat tariff (Rs. 2160/HP/year) for electricity among all Indian states. Agricultural consumption of electricity accounted for only 6.1% of total electricity consumption (WBSEB, 2006) and unlike other states where electricity subsidy form a major share of state fiscal deficits, in West Bengal, this was negligible (Briscoe, 2005).

The state of Uttarakhand in northern part of India was formed in 2001 and earlier was a part of the Uttar Pradesh state. Uttarakhand has an annual net available groundwater resources of 2.10 BCM, of which 66% is being utilized presently (CGWB, 2006). Depth to water table depends on sub-surface lithology and varies from less than 2 m in *Terai* region to as deep at 50 m in the *bhabar* zone. Agriculture uses only 12% of the total electricity in the state, though nearly 70% of all tubewells run on electricity. Till 2007, Uttarakhand too had high flat tariff (Rs. 1512/HP/year) compared to other Indian states, though unlike West Bengal where tariff recovery is very high (more than 90%), in Uttarakhand it is as low as 25% (personal communication with an official of SEB). One of the main reasons for such low tariff recovery is the high tariff rates coupled with periodic waivers of electricity dues by the politicians which lessens the incentive for paying bills in a timely manner. The main irrigated crop in the state is *kharif* paddy and *rabi* wheat. Water markets are less developed as compared to West Bengal, mostly because of larger land holding size which makes it economical for farmers to invest in their own tubewells. Another reason is the wide prevalence of government tubewells, we found that almost every village had a government tubewell and they were functioning satisfactorily.

Gujarat, a western state of India (outside the IG Basin), has an annual replenishable groundwater potential of 15.81 BCM of which 76% (11.49 BCM) is withdrawn every year. This is a state where groundwater is used intensively and 61% of the administrative blocks are over-exploited, critical or semi-critical as per the norms of the Central Groundwater Board (CGWB) (http://cgwb.gov.in/gw_profiles/st_Gujarat.htm). North Gujarat, which on an average receives 500-700 mm of rainfall in a year has deep alluvial aquifers and is a basket case of unsustainable use of groundwater. In many ways, the state of Gujarat epitomizes the groundwater crisis in India. Yet, the state has been registering an agricultural growth rate of 10% for the last 7-8 years and this surpasses that of other states better endowed with water resources (Gulati et al., 2009). Here, farmers have also increasingly moved away from cereal crops to high value crops such as Bt cotton, tobacco, dairy, orchard and commercial crops, so as to maximize value per drop of water. Gujarat also has strong farmers lobbies that have time and again successfully thwarted any attempt to curtail their access to groundwater (Mukherji, 2006). Gujarat, till the recent reforms, had one of the highest electricity subsidies in India. Given the heavy losses sustained by the state electricity board, there was a rapid deterioration of the quality of power supply in the state thereby negatively affecting the quality of life in rural areas. Gujarat, like West Bengal, also supports a vibrant groundwater market. Indeed, groundwater markets in Gujarat predate that of other regions in India (Shah, 1993).

5.3.1.2. The process of reform in three states

Metering in West Bengal and Uttarakhand: The government of West Bengal (GoWB) has adopted a hi-tech approach to metering through the installation of remotely sensed tamper-proof meters which operate on the Time of the Day (TOD) principle, whereby by differentiating the cost of electricity during different times of the day, consumers are discouraged from using pumps during peak evening hours while they are encouraged to do the same during slack night hours. There are three metered tariff rates, namely, normal rates from 6 am to 5 pm (@ Rs. 1.37/unit), peak rates from 5 pm to 11 pm (@ Rs. 4.75/unit) and off-peak rates from 11 pm to 6 am (Re. 0.75/unit). On an average these unit rates translates to around Rs. 6/hour inclusive of Rs. 22/month as meter rent. These new meters solve many of the traditional problems of metering, namely, tampering, under-reporting and under-billing by the meter readers in collusion with the villagers, arbitrary power of the meter readers and the physical abuse that the meter readers were subject to at times at the hands of the irate villagers. Farmers in three districts have started receiving bills based on metered readings and other districts will follow soon.

The government Uttarakhand (GoU) has installed electronic meters, but it has chosen the conventional form of billing which relies on manual billing by the meter readers. No TOD system has been adopted here and metered tariff has been fixed at a low rate of Re. 0.70/unit, which is even lower than the off-peak tariff in West Bengal. This works out to be even much lower than the current flat tariff rates of Rs. 126/HP/month. So far, meters have been installed in 70% of agricultural tubewells, not during our survey, we did not find a single instance where a farmer reported receiving bills based on actual meter reading. The reason for this is paucity of field staff in the electricity department and there are no chances that new meter readers will be recruited in the near future. The electricity department has undertaken some half-hearted efforts at involving village self help groups for meter reading, but we did not gauge much enthusiasm for this among the villagers. On the whole, the farmer leaders, the villagers as well as the electricity department officials believe that metering in its current form is unlikely to succeed and that government would go back to flat tariff system, albeit at even lower rates than at present.

Jyotirgram Yojana in Gujarat: In September 2003, the Government of Gujarat (GoG) pioneered a bold scheme—the *Jyotirgram Scheme (*JGS)—to separate agricultural feeders from non-agricultural ones. JGS was launched initially in 8 districts of Gujarat on pilot basis .The early results were so encouraging that on 17th November, 2004, the scheme was extended to the entire state. By March 7, 2006 over 90 percent of Gujarat's 18,000 villages were covered under JGS. This involved total rewiring of rural Gujarat. In short, under the JGS, the GEB laid a parallel rural transmission network across the state at an investment of Rs.1,170 crore. Feeders supplying agricultural connection were bifurcated from the supply to commercial and residential connection at sub-station itself. Meters on distribution transformer centers were also installed on both the sides of feeders to improve the accuracy for energy accounting.

Pre-JGS, at the lowest level, 11KV feeders served a group of 2-5 villages wherein all connections in these villages (domestic, agricultural as well as commercial) were through this feeder (see Figure 5.2(a). Post-JGS however, the feeders were bifurcated into agricultural and non-agricultural feeders (Figure 5.2(b). This meant that certain feeders only served farm consumers and connections while the rest served the domestic and commercial customers. Meters were installed on each feeder, especially the agri-feeders to identify the source of any *significantly-greater-than-expected* demand at any particular feeder. Rural Gujarat thus rewired, the government put into place a new rural electricity regime that provided high quality, predictable, reliable but *rationed* power supply to agriculture. Under the JGS, then,: [a] the villages began to be provided 24 hour power supply for domestic uses, in schools, hospitals, village industries; [b] farmers began getting 8 hours of daily power supply but of full voltage and on a pre-announced schedule. Every village is to get agricultural power during the day and night in alternate weeks that are pre-announced.

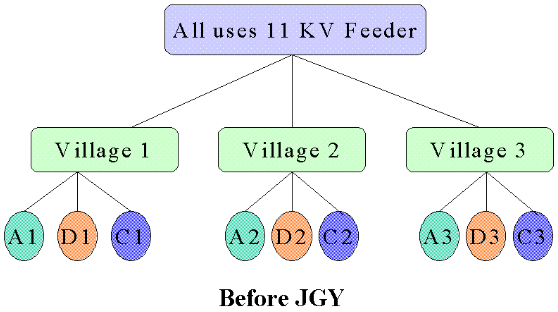


Figure 5.2(a): Electricity network before JGS.

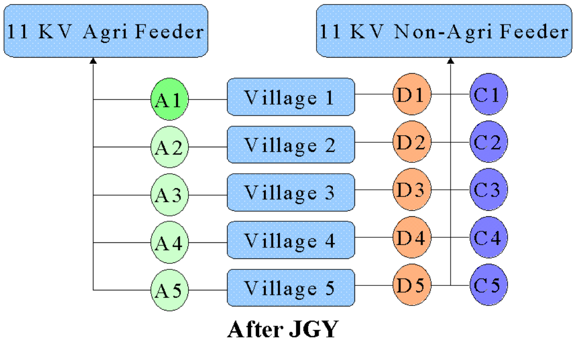


Figure 5.2(b). Electricity network after JGS

5.3.1.3. Impact of electricity reforms on groundwater use, water markets, quality of rural life and electricity boards

Impact of metering in West Bengal: In West Bengal, groundwater markets emerged in response to high flat rate tariff, whereby, the tubewell owners were under pressure to sell water just to recover the electricity bill given their own land holding was not sufficiently large to justify the high electricity cost. This compulsion on the part of tubewell owners also meant that water buyers, who happen to be mostly small and marginal farmers, had sufficient bargaining power over the water seller. That this reasoning is correct is shown by the fact while flat tariff rates increased around 10 fold from 1991 to 2006 (from Rs. 1100/year to Rs. 10,800/year), water price only rose by 6 times from Rs. 300/acre in 1991 to Rs. 1800/acre in 2006 for summer *boro* paddy (Mukherji, 2007). However, metering of electricity supply has changed the very incentive structure and now the water sellers are no longer under a compulsion to sell water because they will pay only for as much as they pump. So, soon after metering, the pump owners have increased the rates at which they sell water by 30-50%. The pump owners have benefitted under the current meter tariff regime in two ways a) by having to pay a lower electricity bill than before for same hours of use b) by being able to charge a higher water price than before and therefore increasing their profit margins for selling water. It is to be noted that there are only 100,000 or so electric pump owners in the state and they constitute less than 2% of the total farming households. It is this small group of wealthier farmers who have benefitted directly from metering. On the other hand, the water buyers have lost out in two ways too a) by having to pay a higher water charge than before b) by having to face adverse terms of conditions of water buying (e.g. advance payments, not been able to get water at desired times etc.). At the current tariff rates and assuming same usage pattern, the SEB too will lose out in terms of revenues, but it may gain through decrease in T&D losses. The actual impact of metering on the size of groundwater markets (i.e. whether they will expand, contract or remain the same) and volume of groundwater extracted cannot be predicted a-priori and has to be answered only empirically (Mukherji, 2009).

Impact of metering in Uttarakhand: In Uttarakhand, under the existing metered tariff rates, all tubewell owners will gain by having to pay less than 1/3rd of electricity bill than they are supposed to pay under the flat tariff rates, but as we found, very few paid anyway. In this state, the main irrigated crops are *kharif* (monsoon) paddy which needs supplementary irrigation and *rabi* (winter) wheat which needs 4-6 irrigations. As such average hour of operation of a tubewell is only 600-800 hours. Informal groundwater markets exist, but they are not as developed here as they are in West Bengal. Almost every village has a government tubewell, most of them constructed after 2001 when the state was formed and as such function reasonably well and supply water to farmers at rates cheaper than private tubewells. Besides, the types of crops grown ensure that there is not a very large demand for water as it is in case of summer paddy in West Bengal. All these reasons explain why groundwater markets are relatively less developed in this state. Metering of tubewells has had no impact on water prices. Water was sold at a rate of Rs. 50/hour before metering, and the same rates continued even after metering. Similar to West Bengal, in Uttarakhand too, the state electricity utility would earn less revenue than before. Given the very low metered tariff rates, it is unlikely that there would be any impact on the volume of water pumped either (Mukherji et al. 2008).

Impact of JGS in Gujarat: By 2006, Gujarat covered almost all its 18,000 villages under the *Jyotirgram* Yojana. This has radically improved the quality of village life, spurred non-farm economic enterprises, halved power subsidy to agriculture and reduced groundwater draft. It has also offered a mixed bag to medium and large farmers but hit marginal farmers and the landless. These depend for their access to irrigation on water markets which have shrunk post-*Jyotirgram;* and water prices charged by tubewell owners have soared 30-50 percent. Table 5.2 summarizes the impact of the scheme on different groups of rural residents, including pump owners and water buyers.

Table 5.2. Impacts of the *Jyotirgram* Scheme on different stakeholder groups.

Stakeholder group	Positive (+)/Negative (-)
Rural housewives, domestic users	**+++++**
Students, teachers, patients, doctors	**+++++**
Non-farm trades, shops, cottage industries, rice mills, dairy co-ops. etc.	**+++++**
Pump repair, motor rewinding, tubewell deepening, etc (Pump mechanics)	**- - - - -**
Tubewell owners: quality and reliability of power supply	**+++**
Tubewell owners: No. of hours of power supply	**- - -**
Water buyers, landless laborers, tenants	**- - - - -**
Groundwater irrigated area	**- - -**

Source: Shah & Verma, 2009

Government figures suggest that farm power use on tubewells has fallen from over 15.7 billion units/year in 2001 to 9.9 billion units in 2006, a nearly 37 percent decline. There is a substantial decline in agricultural power use; and halving of aggregate farm power subsidy, from US$ 788 million in 2001-02 to US$ 388 million in 2006-07. From this, we can infer that annual groundwater use in Gujarat agriculture has declined significantly between the same periods. Finally, from the accounts of all our research partners, the JGS has brought about unprecedented improvement in the quality of life of rural people by creating a rural power supply environment qualitatively identical to urban one. Thus as a broad rural development intervention, JGS is without a parallel. The full import of rationed power supply has yet not been felt by the farmers because 2005 and 2006 were both good monsoon years when wells were full and water levels close to the ground. Come a drought year, and farmers may find the JGS ration of power too meager to meet their irrigation needs.

5.3.1.4. Electricity reforms and groundwater: Implications for institutions and policies

India is in the midst of power sector reforms and states have chosen different pathways to reforms based on their political constituency. While most Indian states have resisted metering of agricultural tubewells, the states of West Bengal and Uttarakhand have embarked upon metering of all tubewells. This study compares and contrasts the initiative of the two states in terms of the process of metering and impact of the same on groundwater use and users (including water buyers). It finds that both states have adopted vastly different attitudes to metering. West Bengal, by adopting hi-tech technology has successfully overcome some of the traditional problems of metering, such as meter tampering, unholy collusion between the meter readers and the villagers, lack of manpower on the part of the electricity utilities etc. However, the state of Uttarakhand has done none of this and has deployed traditional ways of metering and billing. Given their lack of man

power and other logistical difficulties, it is fairly certain that metering efforts will fail in the state. This is quite unfortunate since metering (at existing rates) would have benefitted the tubewell owners without creating any negative effects on the water buyers, who anyway, are few in numbers. In West Bengal, however, metering has benefitted a small section of wealthier pump owners at the cost of majority of small and marginal water buying farmers by changing the very incentive structure inherent in earlier flat tariff system which encouraged pump owners to pro-actively sell water. The main finding of this study is somewhat of a paradox: it shows that where metering could have generated a win-win situation (as in Uttarakhand), the government has adopted a very ad-hoc and ill planned approach to metering, while in West Bengal, where majority of the groundwater users (water buyers in this case) would be harmed, the government has taken a well thought out approach.
In view of this, our recommendations are the following:

i. The GoU should learn from the GoWB example and introduce tamper proof and remotely sensed meters to overcome the problems associated with meter reading and billing. This will of course necessitate additional funds.
ii. In West Bengal, to safeguard the interest of the water buying farmers, the government should ease the process of electrification of tubewells and provide one time capital subsidy for constructing tubewells, especially for the small and marginal farmers. This will lead to increase in number of electric tubewells and enhanced competition in water markets through which water prices may come down in the future. The region has good amounts of annually renewable water resources.
iii. Village level governments (*panchayats*) can play an important role in West Bengal by regulating the price at which water is sold to the buyers.

The *Jyotirgram* Scheme in Gujarat has pioneered real-time co-management of electricity and groundwater irrigation. Its highly beneficial and liberating impacts on rural women, school children, village institutions and quality of rural life are all too evident; its impact on spurring the non-farm rural economy are incipient but all indicators suggest that this will be significant and deepen over time. Thanks to *Jyotirgram*, Gujarat is well on its way to put its electricity industry on a sound footing in just over five years. But above all else, *Jyotirgram* Scheme has created a switch-on/off groundwater economy that is amenable to vigorous regulation at different levels. Elsewhere in India and the rest of the world, groundwater managements have experimented with a diverse set of resource governance regimes—using water laws, tradable groundwater rights, economic incentives and disincentives—to achieve improved groundwater demand management for productivity, equity and sustainability. In their effectiveness, these regimes have proved ineffective, costly and time-consuming. In comparison, Gujarat under JGS has shown that effective rationing of power supply can indeed act as a powerful, indeed all powerful, tool for groundwater demand management. It can be used to reduce groundwater draft in resource-stressed areas and to stimulate it in water-abundant or water-logged areas; it can be used to stimulate conjunctive use of ground and surface water; it can be used to reward 'feeder communities' that invest in groundwater recharge and penalize villages that overdraw groundwater. A big breakthrough is the control government now has on the size of the farm power subsidy, which had spiralled out of control in recent times. As it is managed now, JGS has a big downside: its brunt is borne largely by marginal farmers, and landless because of the shrinking of water markets and of irrigated agriculture itself. JGS can significantly reduce the misery of the agrarian poor by replacing the present rationing schedule by an intelligent, demand-adjusted power rationing.

5.4. Irrigation and Agrarian Tenancy in the IGB: A Rapid Appraisal in 45 Villages across Nepal

Agriculture is the mainstay of the Nepalese economy, providing livelihood for more than 80 percent of the population. Although the share of agriculture in total GDP has been declining over the years, it is still the largest sector of the economy, accounting for 38 percent of GDP in 2006 (MOF,2007). In comparison to many other countries of Asia, the structure of the Nepalese economy has not changed much - the share of agriculture in total GDP fell by only 6 percent over a period of about 15 years from 1990-92 to in 2003-05. Moreover, industrial activities are in its infancy, mostly concentrated in the *terai* along the highways and do not absorb all the work force which is unemployed and underemployed in the agricultural sector.

Growth of the Nepalese economy is determined largely by agriculture sector due to poor industrial base. Out of the total population of 25.9 million (CBS, 2005), some 80 percent reside in rural areas whose main economic base is agriculture. Due to rugged topography, only about 17 percent (2.5

million hectares) of country's total land area is suitable for agriculture; with a cropping intensity varying from 100 to 300 percent depending upon the availability of irrigation. In *terai* about 38 percent of the total land area is cultivated followed by 10 percent and 2 percent in the hills and mountains, respectively. The farm sizes in Nepal have been declining overtime. The agricultural holdings in the country increased to 2.74 million from 1.54 million with average size of holding of 1.11 hectare in 1961/62 to 0.96 ha in 1991/92 due to the increase in population (CBS, 1994:11). Thus, the cultivated land is fragmented into smallholdings and the majority of the farming population has less than one hectare.

Leasehold in the past signified the feudal characteristics of the society. However, the forms of leasehold practices have been changing over a period of time and are different from one ecological region to another. Against this background, a rapid assessment was carried out to know the extent and type of tenancy in relation to the irrigation availability in five districts Kaski (hill), Chitwan (inner *terai*) and Bara, Sunsari and Jhapa (*terai*). The information was collected through structured questionnaire and checklist with the villagers representing various segment of the population in the community.

5.4.1. Extent and drivers of tenant-farming

Nepal's Land Reform Act of 1964 in fact attempted to address landless and tenancy issue through land ownership ceilings and guaranteeing tenancy rights nevertheless, only 1.5 percent of total agricultural land was distributed because of widespread evasion of land ceilings. The Land Reform Act of 1964 established the right of the tenants to one fourth of the land ownership they cultivated. The owner-operated constitute 83 percent of the total holdings, whereas 2 percent of the holdings were under full tenancy (CBS, 1994).

This dual ownership is more prevalent in the *terai* than in the hills and the mountains. This is because of the absentee ownership and those having large chunk of land who have leased out land for cultivation. The National Living Standard Survey NLSS (I and II) revealed that average size of holding has declined in 2003/04 as compared to 1995/96 and the decrease in area owned is largely due to a reduction of farm sizes among farmers in the Terai. The non-farm households and agricultural wage labourers owned significantly smaller size of land; average land ownership among wage labourers is only 0.05 ha.

Landlessness is also one of the primary reasons for tenant farming. Landlessness in *terai* is more acute (18%) compared to the hills (3%). Therefore, the tenancy issue is more important to the farmers in the *terai* than in the hills. Because of this reason, the leasehold practice is more prominent in the *terai* than in the hills. At the same time, the availability of other forms of employment and income opportunities and geographical location also are the determinant factors.

5.4.2. Determinants of terms of tenancy transactions

Three types of renting are prevalent in the country according to the agricultural census of 1991/92 (CBS, 1997). Share cropping (47%) is the most common form of renting followed by fixed quantity of produce (30%) and mortgage arrangement (18%). Mortgage arrangement is the common form of leasing in the hills as compared to share cropping, fixed quantity of produce and contract. This is a contractual arrangement between the farmers and the lender for some period of time. In that case the farmer who lends the money does not receive interests; instead the lender keeps a part of the produce as interest. Share cropping is a contractual arrangement between the owner and the cultivator to cultivate the land on 50/50 share basis, in which the owner provides the land and the cultivator provides the labor. However, the owner and the cultivator share other inputs equally. The cultivator however, does not have the legal tenancy right over the land. The size of holdings is a major determinant on the tenancy practices in the hills. Recent field survey (2008) in the hills and inner terai (Kaski and Chitwan) has revealed the emergence of contract farming, in which the land is leased on contract for specified period on an annual rental basis.

The availability of irrigation is a major factor for determining the terms of tenancy. Therefore, there is a distinct difference across the regions in leasehold practices. The leasehold practice in the hills has declined over a period of time. In both the study sites in the hills, owner cultivation is in practice, in which the owner used to hire wage laborer for cultivation. The field study also indicated that the rain fed land is not leased in the hills and inner terai, as vegetable cultivation on contract is preferred form of lease. The access to the road head and market, especially in the hills is also an important factor for land lease. The presence of large owners and absentee ownership is another important factor for the prevalence of tenancy in the rural areas. Beside, the presence of small holders and land less population in the village is also the determinant of the tenancy practices in the village.

According to the respondents, the trend of leasehold is decreasing due mainly to land fragmentation because of family separation. At the same time the share cropping arrangement between the landowner and tenants is decreasing due to fear of tenancy right claim. Therefore, the landowners in Jhapa in Eastern Nepal instead have been contracting out to the same person who used to share crop before. This has been substantiated from the national level data also, which indicates that the total holding renting land has decreased by 4% during the period 1991-2001 (CBS 2004). Lack of trust between the leaseholder and lessee whether the lessee will pay the agreed rent or not is also cited as one of the reasons for not leasing land especially in *terai.*

5.4.3. Impact of irrigation on land rentals

Farmers' in both the sites in the hills have started leasehold on contract basis and that started only after the availability of irrigation water through rehabilitated irrigation systems. The contract is mainly for vegetable farming and usually for a period of five years, as the lessee would like to ensure maximum return from the investment he will make for land. The lessees are of the opinion that the return from the land is encouraging if managed for 3-5 years. Nevertheless, the rent for the land varies between NRs. 3,000-NRs. 10,000 depending on the availability (year round) and reliability (in time) of the water.

One of the major impacts of irrigation in one of the sites in hills was the in migration to the valley floor from the hills after the rehabilitation of the irrigation scheme for agricultural activities and has started residing close to the farming site. In this site, the agricultural land is being converted to the residential purpose by property developers. The farmer suggest for policy measures to stop irrigated agriculture land being converted to residential purpose. The irrigation policy has this provision but in absence of legal enforcement, this is not effectively implemented.

The leasehold does not apply to rainfed land in both the sites in inner *terai* (Chitwan). The access to irrigation and closeness of the market are the major determinants of the rent in case of inner *terai*. The source of irrigation is shallow tubewell in both the sites and the land irrigated through shallow tubewell powered by electricity commands higher rent than surface irrigation due to reliability of irrigation water. The annual rent of the land varies between NRs. 25,000- 30,000 per ha in which the fruit and vegetable is cultivated. The difference in the rent between two types of irrigation is due to cost of electricity for pump operation for shallow tubewell irrigation. Likewise, the rent in diesel operated pump is lower (Rs. 15,000) because of high cost of diesel.

The agriculture in studied area in *terai* is through canal irrigation, shallow tubewell and lifting water from the river. However, the river is not perennial but monsoon fed therefore, it is a rain fed irrigation. There are three diesel operated shallow tubewells as well but they are seldom used due to high cost of diesel. The rent in *terai* varies between NRs 5,000 and NRs 8,000 according to the quality of land and mode of irrigation. The canal irrigated land command a rent between NRs 11,000 and 16,000 for average and superior quality land, respectively. The other factors that affect the rent are the price of fertilizer and its availability and price paid in hiring tractor for ploughing vis-à-vis quantity of produce and its market price.

To conclude, following observations were made from the study:

i. Having feudal characteristics of landholding where higher caste and a few of them owned large chunk of the land in the past has perpetuated wide gaps between the rich and poor in the rural areas, which had an implication in the tenancy practices.
ii. Landlessness is another important driving force, which is at higher side in *terai*, for the prevalence of tenancy practices. The Land Reform Act of 1964 and its amendment tried to address the landlessness and the tenancy issues. However, it was not successful due to ineffective implementation. The situation was found to be different in the hills, inner *terai* and *terai.*
iii. Mainly three forms of tenancy: mortgage, share crop and contract farming were in practice.
iv. The intensity of leasehold in *terai* is higher than in the hills and inner *terai*. This could be largely due to the presence of landless household and absentee owners.
v. In all the studied area, the leaseholders are the absentee owners, those having alternative employment and households having small plot of land. The lessees are the land less, those having small patches of their own land and households having large family members.
vi. Irrigation is the major determinant in all the studied area for leasehold. Irrigation availability was a must in case of contract farming across all the study sites.

vii. The general trend in leasehold farming in the studied area suggest that new policy changes are required to promote leasehold to address the issues related to landlessness, tenancy and to increase agricultural production and productivity. The policy should encourage consolidation of the farms, investment in assured irrigation and right of tenants.

5.5. Institutional Dynamics of Pond Fishery in the Eastern IGB (Bangladesh)

Institutional arrangements play an important role in productivity of fisheries. Exceptionally high productivity in aquaculture is linked primarily with areas having good institutional set-up, where there is a huge presence of government organizations and NGOs. Strong institutional arrangements in aquaculture include a well-established seed dissemination system and hatchery, where fish seeds are easily and cheaply available. A good example of this is the district of Jessore in Gorai sub-basin. Also, Faridpur has high productivity in *baor* as well as *beel* fisheries, which is again attributed to the institutional arrangements in the area, where the Department of Fisheries (DoF) has an extensive donor assisted effort over the last decade. On the other hand, a weak institutional set up may lead to lower productivity. This is the case in most of the areas, with few exceptions where low productivity is the result of multiple ownership or ownership conflicts.
The institutional dynamism can be classified broadly under 3 categories:

i. Public Institutions e.g. Department of Fisheries (DoF), Bangladesh Fisheries Research Institute (BFRI), Bangladesh Fish Development Corporation (BFDC), Department of Agricultural Extension (DAE), Public bank etc.
ii. Private institutions including NGOs e.g. private hatchery, nursery, fish-farm, processing plant, credit facilitators etc.
iii. Community level/Local Institutions e.g. Water Management Cooperative Association (WMCA), Community Based Organizations (CBO), Resource Management Organization (RMO), market associations etc.

These institutions follow several frameworks with a range of activities for fisheries and aquaculture development, which include:

i. Research and technology innovations-Developing technologies, carrying out feasibility studies,producing manuals for culture technique or management aspects.
ii. Technology transfer and adoption-Training on culture techniques and better management practices, consultation for the improvement of technology dissemination, and commercialization of proven technologies.

5.5.1. Technology impact assessment

In Bangladesh, the premier institution for fisheries technology development is ‘Bangladesh Fisheries Research Institute (BFRI)’. This institute has pioneered and developed many technologies in the field of fish breeding and seed production, fish culture (mono and polyculture, pen culture, cage culture, shrimp culture, crop rotation of shrimp and fish culture), integrated farming, management and policy formulation and biotechnology. On the other hand, state Department of Fisheries has mainly focused on extension services, farming practices, hatchery operations and conservation through District and Upazila Fisheries offices. Bangladesh Fisheries Development Corporation (BFDC) is engaged with marketing and fisheries development function.

Primary surveys during the study revealed that people approach different institutions/ agencies for different reasons. People approached *Upazila Parishad* the most, but circumstantially, as almost half of the farmers approached the institution to collect relief materials after SIDR cyclone. Among other agencies only around 10% of farmers approached State Fisheries and Agriculture office for different purposes. The respondents have also rated the institutions based on the range and effectiveness of the services received on a scale of 1-5, where 5 means active and 1 denotes to extremely poor (Table 5.3). Respondents reported various constraints to access institutional loan. With respect to credit disbursement by NGOs, the interest rates are high and there is at times a requirement to provide a deposit in the form of assets to the credit institution, which in the case of poor farmers is not possible, and therefore they miss their access to credit. The limitations faced by farmers with public financial institutions (i.e. banks) are the demand of an additional and unrecorded amount of money for the disbursement of the loan requested and much delay in disbursement of the loan- often missing the critical time of stock building.

Table 5.3. Efficiency of different institutions on the basis of fishers’ and fish-farmers’ perception at three study villages.

Name of the institution	Chuadanga		Narail		Bagerhat	
	Fisher	Fish-Farmers	Fisher	Fish-Farmers	Fisher	Fish-Farmers
State Fishery Department Office	Moderate	Moderate to active	Fair	Active	Active	Active
State Agriculture Office	Moderate	Moderate to active	Fair	Moderate	Active	Active
Upazila Parishad*	Moderate	Moderate to active	-	-	-	-
*Thana**	Fair	Moderate			Moderate	Moderate
Union Parishad*	Active	Active	Fair	Moderate	Active	Active
NGOs	-	-	-	-	Active	Active
Water Development Board	Extremely poor	Extremely poor	-	-	Active	Active
Other Projects	Moderate	-	-	-	-	-
Private organizations	-	-	-	Active	-	-

*Offices of state administration at different levels

5.6. Laws and Water Resources Governance in the IGB

The purpose of this piece of research was to trace the evolution of water laws and policies in South Asia (IG Basin countries of India, Pakistan, Nepal and Bangladesh). The overall objective of the study is to obtain an overview of how these frameworks have evolved with respect to providing an effective basis for water governance at national, sub-national (in the cases of India and Pakistan) and basin levels. The study is based on the premise that an understanding of the past can provide insights on how the current policy and legal frameworks are poised to evolve in the future, and how they are placed in addressing current needs in the water sector which is in turn a critical pillar of economic and socio-political development.

The study collected a number of important legal and governance documents, carefully studied these with respect to the provisions and objectives, categorised these under different heads and put these under a well-designed framework. The study broadly indicated the following important patterns:

5.6.1. Temporal trends

Figure 5.3 illustrates the exponential growth in policy making and legislation in the IGB over the study period, with a significant increase in activity from the 1990s to date.

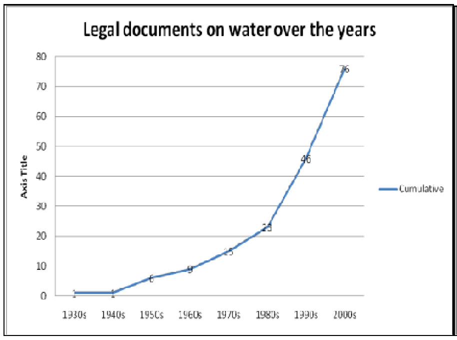


Figure 5.3. Growth of policy and legal the IGB countries

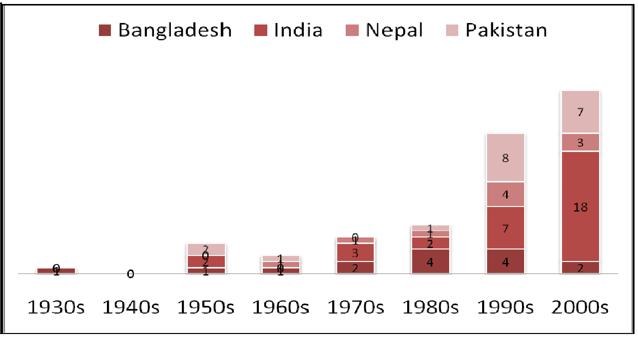


Figure 5.4. Frequency of policy making and legislation in frameworks in the IGB

While the increase in attention to policy and legal frameworks at the national level partly account for this trend, our analysis also indicates the significant contribution of a growing body of sub-national level activity in India and Pakistan (Figure 5.4). Figure 5.5 illustrates the progression of policy and legal frameworks from a focus on water development up to the 1970s after which water management and water governance in particular have assumed prominence.

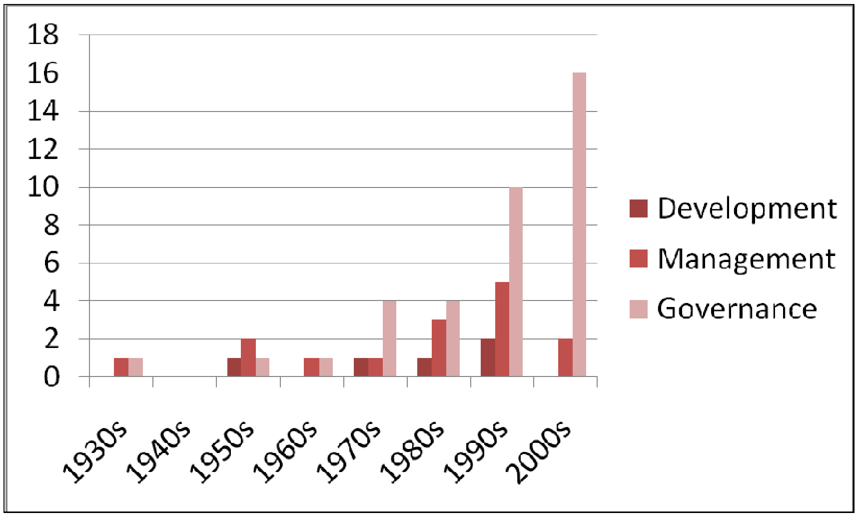


Figure 5.5. Orientation of water sector legal instruments between water resource development, management and governance in the IGB.

The availability of a comprehensive database of Indian legislation organized by year (http://www.commonlii.org/in/legis/num_act/) was used to compare the trend in water sector instruments with the overall legislative activity. Figures 5.6 (a) and (b) show a close resemblance between law making in India as a whole and the water sector, with a significant flurry of legislation in the current decade.

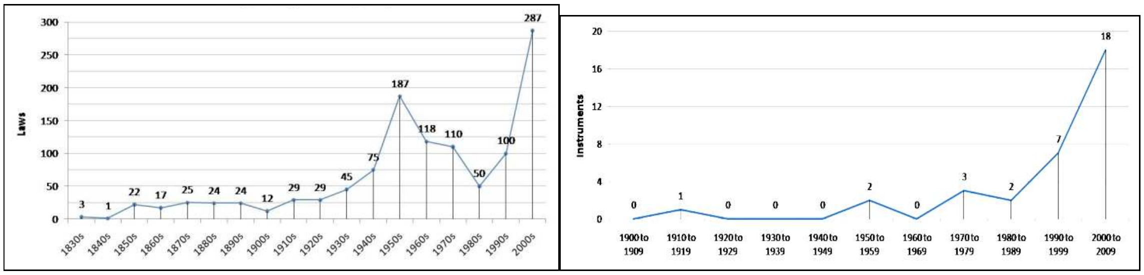


Figure 5.6 (a). Laws enacted in India by decade (b) Water-related laws enacted in India by decade.

5.6.2. Groundwater laws in South Asia

The study undertook a detailed analysis of groundwater laws in India. The main findings are presented in this section. While Figure 5.7 shows the general increase in attention to groundwater across the IGB since the 1990s, the most evident feature is the rise of groundwater as a key consideration in India both at the federal and the state levels.

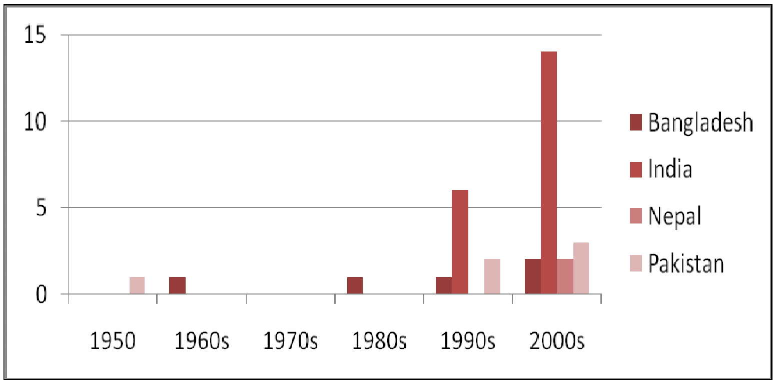


Figure 5.7. Emergence of groundwater policy and legislation in IGB countries.

It is also noteworthy that groundwater featured in 20 of the 25 instruments assessed for India for the 1990-2009 period, with 15 classified as having either a primary or substantial focus (Figure 5.8). However, while this quantitative observation confirms the significant attention given to groundwater, the review of the content of relevant instruments identified a substantial degree of similarity in content (and language) between several of the more recent instruments. This was most prevalent amongst the three federal draft Groundwater Bills (1992, 1996 and 2005) and the close resemblance to the 2005 Bill of the groundwater legislation of West Bengal, Bihar and Himachal Pradesh.

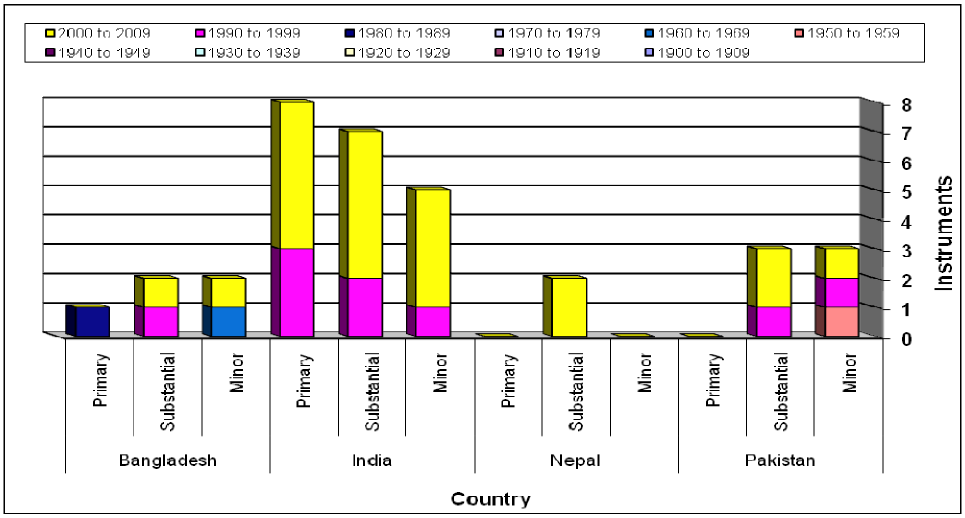


Figure 5.8. Dominance of groundwater laws in India (1990-2009).

In India at the Union level, two trends emerge when considering policies, legal enactments and resource management plans. One is the gradual move towards regulation of groundwater use. The need for limiting extraction within recharge limits was recognised by the National Water Policy of 1987.[1] It also called for a periodical reassessment on a scientific basis of the ground water potential, taking into consideration the quality of the water available and economic viability (Section 7.1). This was followed by the proposed introduction of permits for and registration of new and existing wells,[2] as well as the regulation of commercial well digging, be it in the Draft Groundwater Bill of 1992. The Bill also envisaged the creation of a National Ground Water Authority with the power to advice the State/Union Territory Government to declare any area to be a notified area for the purposes of controlling the extraction or use of ground water in any area and providing licences for further development of groundwater. The Draft Groundwater Bill of 1996 follows many of the provisions of the 1992 Bill, while introducing additional criteria to be considered when evaluating applications for new wells. The exceptions to the need for permits was also amended to include anyone who proposes to install a well that is to be fitted with a hand operated manual pump or water is proposed to be withdrawn by manual devices.[3] The third Draft Groundwater Bill developed in 2005 continues the thinking of its predecessors, and introduces further criteria when reviewing applications for permission to construct wells.

Concerns over groundwater overuse emerge in the National Water Policy of 2002 which states that "overexploitation of groundwater resources in certain parts of the country have raised the concern and need for judicious and scientific resource management and conservation" (Section 6.1). The Policy goes on to require that integrated and coordinated development of surface water and ground water resources and their conjunctive use, should be incorporated from the project planning stage and should form an integral part of the project implementation (Section 7.3).

The second trend and a significant addition in the 2005 Bill is the emphasis placed on enhancing the supply side through groundwater recharge systems. Thus the Bill envisages permits for digging

---

[1] Section 7.2

[2] Small and marginal farmers will not have to obtain a permit if the well is proposed to be sunk for exclusively personal purposes (Section 6.1).

[3] Section 6.1

new wells to include the mandatory provision requiring artificial recharge structures to be built as part of the well (Article 6.3). The proposed Ground Water Authority would also be charged with identifying areas needing recharge, and issuing guidelines for adoption of rain water harvesting in these areas (Article 19.1). The Authority may give directions to the concerned departments of the State/UT Government to include 'Rain Water Harvesting' in all developmental schemes falling under notified areas. In urban areas, falling in notified areas, the Authority may issue directives for constructing appropriate rain water harvesting structures in all residential, commercial and other premises having an area of 100 m^2 or more in manner prescribed. Community participation through watershed management was identified as another means of facilitating ground water recharge in rural areas (Article 19.1). This is to be supported by the promotion of mass awareness and training programs on rain water harvesting and artificial recharge (Article 19.3).

The states of West Bengal,[4] Bihar[5] and Himachal[6] have closely followed the 2005 Bill. The similarity in structure and context of these enactments suggests an almost total transposition of the 2005 Bill. While this shows a continuum between the centre policies and the states, it also shows the mismatch between groundwater resource conditions and laws governing those resources.

In Bangladesh, permits for wells were introduced by the Ground Water Management Ordinance of 1985 (Article 5.1). The Bangladesh National Water Policy of 1999 calls for preserving natural depressions and water bodies, underground aquifers (Section 4.6b) and the prohibition of filling of publicly-owned water bodies and depressions in urban areas (Section 4.12e). It also encourages massive afforestation and tree coverage specifically in areas with declining water table (Section 4.12h), and proposes the regulation of extraction in identified scarcity zones (Section 4.3c).
The primary concern with groundwater in Nepal has been the dependence of large industries on groundwater extraction through DTWs and the need to regulate this use through licensing and effective monitoring (Section 4.2.2.4, National Water Plan, 2002).

The approach to groundwater management in Pakistan appears to be area-specific. The Draft National Water Policy (date unknown) promotes groundwater recharge wherever technically and economically feasible (Policy 8.4), and calls for the evaluation of various technologies being used for undisturbed extraction and skimming of fresh groundwater layers overlying saline water. It calls for optimal groundwater pumping in waterlogged areas to lower the water table ((Policy 8.7), while areas with falling water tables are to be delineated for restricting uncontrolled abstraction (Policy 8.8). In Baluchistan in contrast, the Draft Baluchistan IWRM Policy (2004) stipulates that groundwater development will be restricted to basins with potential for development, and bans new agri-tubewells in the 3 overdrawn basins (Section 3). Other restrictions include the recommendation that new tubewells for drinking water only to replace existing dry ones, and that in basins where there is limited development potential, only replacement of dried agri-tubewells should be allowed (Section 3).

Overall, the importance given to groundwater in water legislations shows the importance of this resource in the overall water resources in the region.

---

[4] West Bengal Ground Water Resources (Management, Control and Regulation) Act, 2005

[5] Bihar Groundwater (Regulation & Control of Development and Management) Act 2006

[6] Himachal Pradesh Ground Water (Regulation and Control of Development and Management) Rules 2006

6. INTERVENTIONS FOR IMPROVEMENT OF WATER PRODUCTIVITY IN IGB REGION

Bharat R Sharma, Rajendra Singh, Asad Qureshi, G. Ambili, Dhruba Pant, M.G.Mustafa, S.Hervas, M.G.Khan, M.Rahman

Over the years the Indo-Gangetic basin has witnessed a major shift in the cropping pattern and utilization of its water resources. With an exponential growth in area under paddy cultivation and the unsustainable exploitation of groundwater resources in the Indian and Pakistan Punjab, Haryana, western Uttar Pradesh and parts of Rajasthan state the water tables have started declining dramatically. At the same time these regions are pivotal to the food security of their respective countries and surplus food produced in these states meet the food deficit of the other regions. The intensive irrigated production of rice and wheat cereals at a high level (10-12 t/ha) with limited water resources is becoming hydrologically unsustainable with each passing year. State water balances of this region are in negative and the trend is continuing unabated. On the other hand, relatively abundant water resources available in the eastern part of the basin remain inadequately developed and underutilized and the prevalent farming systems have very low land water productivity (*refer Chapter 4*).

There have been a wide variety of potential physical, crop-related and policy interventions tried throughout the IGB but with varying degrees of success. Intervention analysis work package aimed to identify, prioritize and assess a set of such interventions which has the potential of significantly improving productivity and livelihoods under varying agro-ecologies of IGB.

6.1. Development of Intervention Matrices and Prioritization of Crop-production Interventions

Identification of important interventions related to water productivity for the IGB to exploit them for improving water productivity had the following work elements:

6.1.1. Definition of interventions and development of master intervention matrix

The following key intervention categories were selected to identify possible causes of poor water productivity and seek potential solutions for improving water use efficiency in different parts of the IGB:

i. Resource conservation technologies(RCTs)
ii. Water and watershed management
iii. Integrated farming systems
iv. Multiple-use water schemes (MUS)
v. Climate change and environmental flows
vi. Institutional interventions
vii. Land use changes

Key interventions identified under each of the above mentioned categories are given in Table 6.1. A master matrix was prepared for collecting individual information regarding location, coverage, primary purpose, financial implications; specific impacts related to agriculture production, natural resources and livelihood improvements and any other relevant information for each of the intervention. Extensive literature survey (both internet and physical search) was done to collect information available on water productivity in the IGB.

Table 6.1. Intervention categories and interventions for improvement of water productivity in IGB region.

Resource conservation techniques	Water & watershed management	Farming systems	Multiple-use water scheme	Climate change & environmental flow	Institutional interventions	Land use changes
Mulching	Canal lining	Precision farming	Agri-aquaculture	Climate change	Subsidy	Urbanization
Land levelling	Water harvesting structures	Organic farming	Hydroponic horticulture	Water use pattern	Loan waivers	Special Economic Zones (SEZ)
Surface seeding	Pressurized irrigation system	Hybrid seeds	Reuse of urban effluent	Environmental flow requirement	Support price	Extent of land degradation
System of rice intensification	Surge irrigation	Horticultural systems	MUS for hilly areas		Other Governmental policies	
Bed planting	Irrigation scheduling	Crop diversification				
Zero tillage	Deficit irrigation	Livestock systems				
Reduced tillage	Rain water harvesting					
	Groundwater recharge methods					

6.1.2. Development of intervention matrices and data review

Initially 289 matrices covering seven different intervention categories were developed (Table 6.1). Since relevant data were not available in two categories, i.e., Land Use and Institutional Interventions, the focus was centered on the remaining five categories. During the process of developing these 289 matrices, the following observations were made:

i. Mostly, the resource conservation technologies (RCTs) and farming system intervention categories contained data related to water productivity, i.e., yield and water use, though most of these studies were conducted in experimental farms.
ii. In most cases, data related to area covered, number of farmers and/or villages benefited, total irrigated area and total reclaimed area were not available.
iii. Though around 201 studies were collected under water and watershed management category, most of them lacked data on agricultural and related impacts.
iv. In most studies, data related to coverage and financial aspects sub-categories were not available for all the interventions except water and watershed management.
v. Yield and water use data were not available in studies collected under ‘climate change & environmental flow’ intervention category.
vi. Most importantly, most of the studies did not have hard data that may be used to estimate water productivity. Only, twenty-five research papers and 3 PhD theses contained yield and water use data.
vii. There was no consistent approach for reporting water use data. Some of the preferred quantities for water use were: rainfall amounts, rainfall plus irrigation amounts, irrigation amount alone, actual evapo-transpiration, soil water depletion, pan evaporation, consumptive use, water-use efficiency, total water use, etc.

Thus, although it was not possible to get a spatial and crop-specific dataset on water use and yield, these 289 matrices provided an exhaustive list of interventions, which helped in formulating the next step of intervention analysis.

6.2. Identification of Potential Intervention Using Analytical Hierarchy Process

Identification of potential intervention using Analytical Hierarchy Process (AHP) involved following steps:

i. Estimation of water productivity indices
ii. Water productivity for interventions and crops
iii. Intervention Ranking using Analytical Hierarchy Process (AHP)

6.2.1. Estimation of water productivity (WP) indices

Several water productivity (WP) indices corresponding to different water inputs, e.g., actual evapo-transpiration (AET), soil water depletion, irrigation, rainfall, pan evaporation and total water use were estimated for different interventions for several crops using the yield and water use data available in 28 different studies. Table 6.2 shows different ranges of three selected WP indices for different interventions and crops. Both maize and wheat appear to have a wide range of WP values as compared to rice suggesting these two crops would be more amenable to productive interventions. In other words, it may be possible to easily identify an appropriate intervention for improving water use efficiency in these two crops. On the contrary, narrow WP ranges for legumes and oil seed crops suggest that these crops perhaps require more careful management practices for improving water use efficiency compared to cereal crops.

6.2.1.1. Water productivity for interventions and crops: For identifying most efficient water user, WP values for each crop were averaged over different interventions. Crop-wise mean WP values, based on total water use, irrigation water use and AET are shown in Figure 6.1. The figure shows that sugarcane appears to be the most efficient crop with highest mean WP values calculated based on total water use and irrigation water use data. Mean WP based on actual evapo-transpiration was highest for Indian mustard followed by wheat and rice. WP values were also sorted crop-wise to identify the relative importance of different interventions influencing WP for different crop species. However, it was not possible to identify potential interventions based on such analysis because of the lack of statistically acceptable sample size.

Table 6.2. Estimated water productivity values (kg/m$^{3)}$ under selected studies for different crops in IG basin.

	Interventions	Crops	WP-Water use	WP-AET	WP-Irrigation
i.	Irrigation levels, irrigation scheduling	Rice	--	--	0.43-0.81
ii.	Tillage, irrigation regime, mulching, season	Maize	--	--	0.04-6.13
iii.	Tillage	Wheat, Rice	0.26-1.76	--	0.40-3.11
iv.	Raised bed, crop sequence	Chickpea, Linseed, Safflower	0.32-0.77		
v.	Water productivity analysis (SWAP/WOFOST)	Wheat, Rice, Cotton	--	0.22-2.23	---
vi.	Cropping system, nutrient management	Wheat, Rice, Pigeon pea	--	--	0.31-1.34
vii.	Model simulation (WTGROWS & Info Crop)	Wheat	--	--	0.67-3.80
viii.	Transplanting date, cropping system	Rice, Wheat	--	0.80-1.39	0.18-0.31
ix.	Transplanting date, variety	Rice	0.33-0.54	0.95-1.05	0.42-0.78
xi.	Tillage, irrigation regime, mulching, season	Maize	--	--	0.04-6.13
xii.	Tillage, irrigation regime, nitrogen levels	Wheat	0.26-1.76	--	0.12-3.20
xiii.	Raised bed, crop sequence	Chickpea, Linseed, Safflower	0.32-0.77		
xiv.	Transplanting date, cropping system	Rice, Wheat	--	0.80-1.39	0.18-0.31

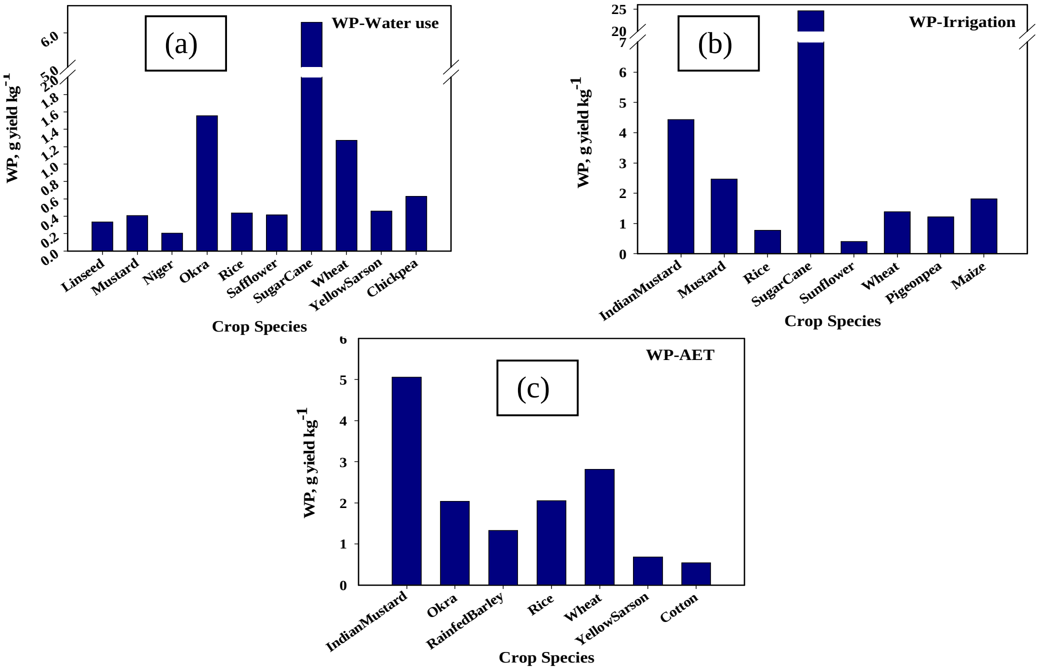


Figure 6.1: Crop-wise mean water productivity based on (a) total water use, (b) irrigation water use and (c) actual evapo-transpiration (AET).

6.2.2. Intervention ranking using Analytical Hierarchy Process (AHP)

Analytic Hierarchy Process, originally developed by Saaty (1980) was used for ranking of interventions. The AHP involves the following steps: breaking an unstructured situation into its component parts; arranging the parts or variables into a hierarchic order; assigning numerical values to subjective judgments on the relative importance of each variable; and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation. Eight different crops were selected for preparing questionnaire considering the major cropping systems followed in the IGB (Biswas et al., 2006).

Crop-specific multiple interventions important for improving water productivity were identified based on the crop-wise sorted water productivity values and literature review of the crop specific agronomic package of practices for the IGB. Questionnaires for different crops were prepared for intervention ranking and sent to 216 experts/stake-holders including 88 scientists, 18 government officials, 106 farmers and 4 NGOs covering the whole IGB for their opinion.

A sample of expert opinion is given in Table 6.3, where each intervention is given a rank from 1-10 for rice crop. The AHP analysis was carried out in the following manner. First, these assigned ranks were converted into weights by reversing the order, i.e., rank 1 was reordered as weight 10; rank 2 was reordered as weight 9 and so on. Then a pair-wise comparison matrix was prepared, which was subsequently solved using the Eigenvector analysis approach. A consistency ratio was also estimated in order to find out the bias and inconsistency of the decision maker.

Table 6.3. Sample of expert opinion for improving water productivity of rice crop in IGB.

Interventions		Weight
i.	Zero Tillage (ZT)	1
ii.	Direct seeded Rice on raised bed (DSR)	9
iii.	Transplanted Rice on raised bed (Bed planted system) (TPR)	10
iv.	Direct Seeded Rice on flat bed (DSF)	8
v.	Crop diversification with Legume-Extra Short Duration Pigeonpea with Furrow Irrigated Raised Bed planting technique (CLP)	4
vi.	Crop diversification with legume-Chickpea with Furrow Irrigated Raised Bed planting technique in sequence and inter cropping (CLC)	5
vii.	Irrigation scheduling and regime (ISR)	6
viii.	Selection of short duration (early transplanting) and photoperiod sensitive (delayed transplanting) cultivars (SD)	3
ix.	Cultivars for Direct Seeded Rice (CDSR)	7
x.	Co-Cultured Sesbania with Direct seeded rice on raised beds (CCS)	2

Saaty (1980) suggested that if consistency ratio (CR) > 0.10 then weight should be re-evaluated. Random Consistency Index values were taken from Saaty (1980) (Table 6.4). For the sample expert opinion shown in Table 6.3, the consistency ratio was calculated to be 0.0037, which was less than 0.01. As per Saaty (1980), weights assigned by this expert were consistent.

6.3. Potential Interventions for Selected Crops

Using the approach outlined above, AHP analysis was carried out for all the expert opinions collected through sample survey and interventions were ranked for each crop. Table 6.4 presents the ranked interventions for rice crop. As per the expert ranking for rice, crop diversification with legume-chickpea with 'Furrow Irrigated Raised Bed (FIRB)' planting technique in sequence and intercropping was identified to be the highest-ranked and 'Zero Tillage' was identified to be the lowest ranked intervention for rice. Table 6.5 presents the top three ranked interventions for the selected crops grown in IGB. Besides crop diversification with legume-chickpea with furrow irrigated raised bed planting technique in sequence and intercropping, the other two important interventions for rice were 'Transplanting on raised bed (Bed planted system)' and 'Cultivars for direct seeded rice'.

Table 6.4. Ranked interventions for improving water productivity in rice in IGB.

Interventions	Rank
i. Crop diversification with legume-chickpea with furrow irrigated raised bed planting technique in sequence and intercropping	1
ii. Transplanted rice on raised bed (Bed planted system)	2
iii. Suitable cultivars for direct seeded rice	3
iv. Selection of short duration (early transplanting) and photoperiod sensitive (delayed transplanting) cultivars	4
v. Direct seeded rice on raised beds	5
vi. Proper irrigation scheduling and moisture regime	6
vii. Direct seeded rice on flat bed	7
viii. Crop diversification with legume-extra short duration pigeon pea with furrow irrigated raised bed planting technique	8
ix. Co-cultured *Sesbania* with direct seeded rice on raised beds	9
x. Zero tillage	10

Table 6.5. Three most important interventions for improving water productivity of selected crops of the IG basin.

Crops	Interventions	Rank
Rice	Crop diversification with legume-chickpea with furrow irrigated raised bed planting technique in sequence and intercropping	1
	Transplanted rice on raised bed (Bed planted system)	2
	Use of suitable cultivars for direct seeded rice	3
Wheat	Use of 100% dose of nitrogen and phosphorus + FYM/Gypsum/Sulphitation Pressmud under No Till practice	1
	Timeliness in sowing operation-sowing by 3rd week of November	2
	Proper irrigation scheduling and moisture regime	3
Maize	Use of hybrid seeds	1
	Cultivation on permanent raised bed planting system	2
	Proper irrigation scheduling and moisture regime	3
Sugarcane	Proper irrigation scheduling and alternate or skip furrow method	1
	Timeliness in planting operation	2
	Furrow planting	3
Pulses	Crop diversification-short duration *Mung bean* as summer crop	1
	Multi-crop zero-till-drill cum bed planting	2
	Crop diversification-chickpea and lentil in rotation with wheat	3
Oilseeds	Selection of suitable cultivars and hybrid seeds	1
	Laser land levelling	2
	Crop diversification-intercropping- Indian mustard+ sugarcane	3
Potato	Planting with quality seed	1
	Proper irrigation scheduling and moisture regime	2
	Basal application of Farm Yard Manure	3
Tomato	Integrated pest management	1
	Use of quality seed and seedlings	2
	Integrated nutrient management	3

The study has shown that the potential interventions for improving water productivity varies with the crops. Proper irrigation scheduling is identified to be the potential intervention for crops like sugarcane, potato, maize and wheat. Use of hybrid seeds, quality seeds and the selection of suitable cultivars are potential interventions for crops such as maize, potato and oilseeds. Crop diversification with legumes and their suitable cultivars is the potential intervention for rice and pulses. Cultivators are required to apply the exact amount of water needed and the frequency at which irrigation has to be applied as parts of irrigation scheduling. More importantly, information on critical growth stages for specific crops in different regions should be made available to farmers so as to facilitate proper irrigation scheduling. Similarly, up-to-date knowledge on crop diversification, hybrid seeds, quality seeds, suitable cultivars and integrated nutrient management are needed for the farmers for implementing the potential interventions to improve water productivity.

6.4. High Potential Interventions for Improving Water Productivity in IG Basin

Improving physical water productivity in agriculture and especially through conservation agriculture reduces the need for additional water and land in irrigated and rainfed systems and is thus a critical response to increasing water scarcity, including the need to leave enough water to sustain ecosystems and to meet the growing demand of cities and industries.

6.4.1. Resource conservation technologies (RCTs)

Since irrigation constitutes the single major consumer of water in IG basin, irrigation water savings would serve as a promising demand management option and help reducing the supply-demand gap. RCTs have significant implications in water savings and productivity improvements, particularly in the case of arid and semi arid regions in the north-western part of the basin where water availability is a constraint in agricultural production. RCTs emphasize on minimum disturbance to soil and retention of residues on the soil surface and have made a significant change in the farming systems in adopted regions. Technologies promoted in IGB include reduced/zero tillage, laser land levelling, raised bed planting and direct seeding of rice, practiced either individually or in combination. Among these, zero tillage (ZT) in wheat and laser land leveling are the most popularly received technology in this region.

Water savings by ZT are brought about by effective utilization of residual soil moisture (12% more utilization, Sikka *et* al., 2005) coupled with the reduction in number of irrigations per season. In the rice-wheat system of Rechna Doab in the Indus basin (Pakistan), farmers reported a 24% decrease in field level water application after adopting zero tillage. Corresponding fuel savings were reported to be 52%, which implies that groundwater pumping might also had been reduced considerably (Ahmad *et al*., 2007). Water productivity increases at field level, where different RCTs are being practiced are given in Table 6.6. These water savings are the combined results of yield increase as well as reduced irrigation applications. The question of whether savings in field level water applications are being scaled up to a larger system, sub-basin or basin-scale is still not fully understood. Medium and large farmers generally tend to increase their cropping intensities, thereby actually increasing the farm level water use, but not so in the case of small farmers (Ahmad *et al.,* 2007). Yield gains from this increased cropping intensity may sometimes reflect as higher water productivities, but at the cost of saved water. In Rechna Doab, large farmers own about 50% of the cultivated area and hence water savings at field level might not be scaled out to the farm level. But when land is a constraint in agricultural production, the productivities get summed up at farm level. However, water savings by reducing flows to saline groundwater sinks, as in central and southern parts of Rechna Doab with high levels of groundwater salinity, could be translated to real water savings from field to higher levels. Whether or not RCT can address the sustainability concerns of water use is still debatable, on account of its impact dimensions at a broader spatial scale.

Table 6.6. Water productivity improvements in rice-wheat systems of IGB by different RCTs (based on published literature).

Technology/ Location	Irrigation water productivity (kg/m^3)	Percentage increase (from conventional)
i. Zero tillage		
Haryana[a]		
Canal	3.69	33.2
Groundwater	2.23	21.5
Mona Project, Pakistan[b]	1.43	30.0
Sheikhupura district, Pakistan[c]	3.00	19.5
ii. Bed planting		
Sheikhupura district, Pakistan[c]	2.98	18.7
Mona Project, Pakistan[b]	1.81	64.5
iii. Laser land levelling		
Modipuram, India[d]		
Laser land leveling (wheat)	1.31	59.8
Laser leveling+ Raised bed (wheat)	1.90	37.7
Laser leveling (rice)	0.91	65.5
Mona project, Pakistan[b]	1.67	51.8

Source: [a] Erenstein et al., 2007 (from water user survey). [b] Hobbs and Gupta, 2007. [c] Jehangir et al., (2007) [d] Jat et al., (2005)

6.4.2. Improved irrigation methods

Improved methods of irrigation have large potential for water conservation and improved productivity. With drip irrigation, in most cases, water savings of 25-80% have been reported. Recent studies by IWMI (Kumar et al., 2008) show that states in the IGB have large areas and crops amenable to drip irrigation with 1.884 m ha in Uttar Pradesh, 0.192 m ha in Bihar, 0.6 m ha in Punjab and 0.374 m ha in Haryana state (Table 6.7). Similar areas also exist in the Indus basin of Pakistan and Nepal terai.

Table 6.7. Aggregate reduction in crop water requirements possible with drip irrigation in India.

Name of crop	Water productivity (kg/m^3)	Improved water productivity (kg/ m^3)	Reduction in crop water requirement (BCM)
Sugarcane	5.950	18.09	31.00
Cotton	0.303	1.080	10.42
Groundnut	0.340	0.950	1.453
Potato	11.79	17.21	0.127
Castor	0.340	0.670	0.497
Onion	1.544	2.700	0.963
Total			**44.46**

6.4.3. Multiple Water-Use Schemes (MUS) in hill areas.

Short and sloping terraces and the insufficient availability of water were not suitable for the development of surface irrigation in the hills of IGB and required development of non-conventional form of irrigation including various improved technologies (low-cost drip irrigation, sprinkler irrigation, pond irrigation, and treadle pump) and the innovative MUS practice. MUS practice has been successfully implemented in the hilly areas of Nepal. In order to address the household water need for production and domestic use, International Development Enterprises (IDE) and International Water Management Institute (IWMI), with some modifications to the conventional piped water systems designed a new hybrid scheme in 2001(Mikhail and Yoder, 2009). The scheme, known as MUS includes one Thai Jar of 3,000 litres for drinking water and the overflow from this jar is collected in an underground tank of 10,000 litres for irrigation through off-takes at farmer's field. The available water was made available to each household for domestic and productive purposes. Water was applied to homestead gardens through simple drip systems

(Sharma et al.; 2010). One of the primary objectives of the introduction of new technology was to increase household income through sale of the surplus vegetable produce in the market. This was further expanded with funding support from USAID by IDE/Nepal and Winrock International through Smallholder Irrigation Market Initiative. The works carried out under the project show that these small-scale schemes have the following advantages:

i. Cost effective in supplying water to remote areas.
ii. Flexibility in its adoption in different locations.
iii. Water supply both for household use (consumptive) and for micro-irrigation of high value crops (productive).
iv. Adopted technologies are suitable for the difficult terrain of hilly regions.
v. Low construction and maintenance costs.
vi. Reduced need for expensive storage tanks.
vii. Significant financial incentives for farmers to install and maintain due to income from high value cash crops.
viii. Reduction in drudgery, empowerment of the women and participation of the communities.

The MUS expansion was possible also due to the partnership developed between government agencies, local elected institutions I/NGOs, CBOs and private parties. This has had positive implication on the growth of MUS, as farmers had to contribute less in cash and kind; they were encouraged to install MUS. In principle, MUS are designed to cover 10 to 40 households but in some cases up to 80 households have been provided service from MUS and the first priority is for the supply of the water for domestic use. This largely depends on the number of households to be served and the availability of water. The design criteria of MUS assume 45 litre/person/day for domestic use and 400-600 liter/household for productive use. Therefore, whether to design a single storage tank or the two storage tank is decided by the technicians in consultation with the users in the community, who know if the water availability is perennial or seasonal.

Estimates showed that the average cost of the system per household is US$ 100 that includes both cash and kind component and the additional benefits through sale of surplus vegetables were able to meet the cost in first year itself, and thus was very attractive (Sharma et. al., 2010). With the introduction of MUS, the households have been producing high-value vegetables and about 90 percent of the vegetable is sold in the market. The schemes also effectively met the drinking and sanitation water requirements of the households, reducing drudgery and incidence of water borne diseases and empowering women for taking strategic household decisions.

6.4.4. Water saving through watercourse improvements: The case of Indus Basin Irrigation System (IBIS)

Low water productivity has been a serious problem in the large Indus Basin Irrigation System and one of the identified factors was very high conveyance losses of the system. To address this issue, recently the Government of Pakistan launched a massive watercourse improvement and rehabilitation program throughout Pakistan in order to control excessive seepage from the unlined and poorly maintained watercourses throughout the country. The National Program for the Improvement of Watercourses (NPIW) with an overall budget of US$ 1.1 billion (2004 cost estimate) was expected to be completed in four years. Under this project, a total of 28,000 watercourses will be improved in canal irrigated areas in Punjab. We briefly studied the impact of the program.

6.4.4.1. *Impact of watercourse improvement on delivery efficiency:* Watercourses improved under the On Farm Water Management (OFWM) program (under the USAID and IDA/IFAD projects) remarkably improved water delivery efficiencies (Table 6.8).

Table 6.8. Improvement in delivery efficiency (%) as a result of watercourse improvement (USAID project, Pakistan).

Project	Delivery efficiency of main water course[1]				Overall delivery efficiency[2]			
	Head	Middle	Tail	Average	Head	Middle	Tail	Average
Pre-Improvement	76	71	63	70	66	63	54	61
Post-Improvement	82	81	74	80	79	73	64	72

[1] Efficiency of the section between *mogha* and *farm nakka*
[2] Efficiency of the section between *mogha* and *field nakka*
(*mogha:* watercourse outlet*; nakka:* farm gate outlet*)*

6.4.4.2.Impact of watercourse improvement on irrigation time and farming practices

Before improvement of watercourses, average time taken to irrigate one hectare of land irrespective of farm size at head, middle and tail sections of a watercourse was 4.5 h, 6.75 h, and 5.25 h, respectively. After the watercourse improvement, adequate supplies were ensured to the farms and the average irrigation time was reduced to 3.5 h, 4.0 h, and 4.25 h at head, middle and tail sections, respectively. This corresponds to 22%, 40% and 19% saving of irrigation time at head, middle, and tail reaches of the watercourse, respectively.

The saving of water due to watercourse improvement had a positive impact on cropping intensities of the command area. Different sizes of farms located at head, middle and tail of the sample watercourse had pre-improvement cropping intensities of 115, 121 and 115%, which were increased to 138, 151 and 132%, respectively after improvement of the watercourses.

6.4.5. Policy intervention for savings in rice water use: Punjab Preservation of Subsoil Water Act, 2009

Agricultural productivity in IGB is largely dependent on groundwater, and as such the resource is under serious threat of over-exploitation especially in the western parts of the basin. Energy and price support policies favor cultivation of water-intensive rice in these groundwater stressed areas. Promulgation of the "Punjab Preservation of Subsoil Water Act, 2009" by Punjab State Government, which makes it mandatory for paddy to be transplanted only after June 10, is one such initiative at the policy side intended to have a check on continuously depleting groundwater environment, but at the same time with promising potential for real water savings through reductions in non-beneficial ET. The analysis has revealed that this water management option could bring about a water savings of around 2,100 MCM, if adopted in the whole rice sown area of Punjab (Fig. 6.2).

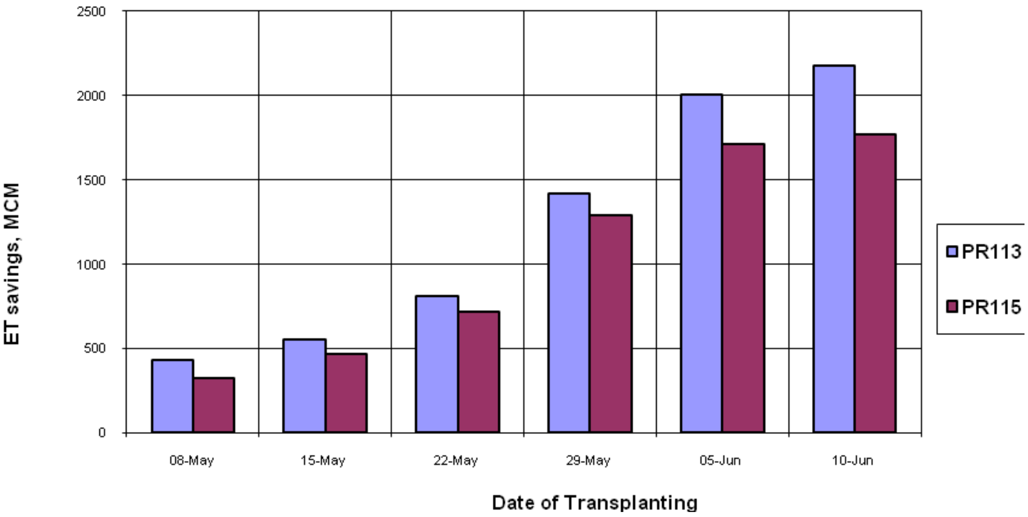


Figure 6.2. Savings in water by delayed transplanting over total rice area in Punjab for two rice varieties (PR113 and PR115).

Experimental results indicating high grain yields with favorable temperature during tillering stage, also warrants water productivity rise. The positive externality associated with this water saving could be a check in water table decline, which is anticipated to be in the range of 60-65% by a decrease in total water requirement by 26-30 cm. The nexus between water-energy-agriculture suggests this water savings will have positive impacts on agricultural energy consumption as well. The study estimated energy savings of upto 175 KWh by checking real water losses. Since the practice reduces non-beneficial water loss, which does not contribute to the output, spatial extrapolation to higher (system, basin, regional) scales would have a positive effect on water productivity. Growing rice in periods of low ET demand coinciding with the onset of monsoons would, therefore, assure 'wet water savings' in arid and semi-arid rice-growing areas of IGB, where groundwater is under severe stress. Cultivation of short duration varieties (like PR115) with comparable yield levels will yield higher water savings.

6.5. Potential Interventions for Improving Fisheries Productivity in Eastern IG Basin

Based on the perception of fishers (capture fisheries) and fish farmers (culture fisheries) and also on professional and expert judgment, the following have been identified as potential interventions for improving fisheries productivity in Gorai-Madhumati sub-basin of Bangladesh but shall be equally valid for other parts of the basin with similar agro-hydrology and socio-economic conditions.

6.5.1. Capture/open water fisheries system

i. Conserve and develop additional fish sanctuaries followed by habitat restoration and management, which have wider beneficial impact on fisheries productivity.
ii. Leasing system of public water bodies need to be improved to enhance productivity and for sustainable fisheries. This is already being attempted in the new Wetland Policy (2009) to take a pro-poor and decentralized implementation system including the provision of longer term duration of leasing and that have to follow the Community Based Fisheries Management guidelines.
iii. Move away from standardized training programs to demand oriented ones, which focus on specific systems or community needs.
iv. Agriculture policy needs to be integrated and synchronized with the other natural resource policies e.g. water policy, fisheries policy, environment policy; those which advocate for mechanisms to enhance ecosystem productivity for both fisheries and other aquatic natural resources in order to maximize water use as well as benefit the society and in particular household with multi-livelihood options.
v. Construction of decentralized community cold storage system for storing fish may be examined to improve the marketing and reduce spoilage of fish produce.

6.5.2. Semi-closed and closed (pond) culture system

i. Community based fish culture and management in large open and semi- closed water-bodies needs to be encouraged to make good use of the low productivity resources.
ii. Hatchery, nursery and feed mills should be established more evenly throughout the sub-basin as demand for inputs is high throughout but mostly available in a concentrated area. Furthermore, government established (but non functional) hatcheries and farms need to be made functional to help meet the demand.
iii. Fish-depots and processing plants should also be facilitated more evenly across the sub-basin as its demand grows from downstream to upstream, whereas the availability is concentrated down to middle stream only.
iv. Strengthening marketing linkages would improve the profits of small producers through smarter supply chains.
v. Decentralized fish seed technology extension can minimize input costs for production and improve local communities' livelihood.
vi. Extension services should be strengthened up to union level by increasing sufficient skilled manpower.

6.5.3. Shrimp and coastal aquaculture

i. These culture systems should develop into more sustainable and environment- friendly technologies.
ii. Ensure quality of fingerling and post larvae by guaranteeing the availability of high quality and high yielding variety of the brood.
iii. Specialized extension services should be strengthened up to union level by increasing aquaculture -skilled manpower.
iv. Due to the commercial nature of shrimp farming, the facilitation of credit support is a pre-requisite and could benefit the interested fish farmers.
v. Introducing salt tolerant varieties will provide adaptation measures for the coastal regions experiencing salt intrusion, which is predicted to increase with the changing climate. Deep-water rice variety along with fish seems to be a win-win option.
vi. Registration of shrimp farm may be made mandatory to avoid management conflicts.

7. WATER-LAND-POVERTY NEXUS IN THE INDO-GANGETIC BASIN

U.A. Amarasinghe, S.Xenarios, G. Ambili, R. Srinivasulu, Atul K Singh, D. Pant, A. S. Qureshi, and M. Samad

7.1. Poverty in the Indo-Gangetic Basin

Indo-Gangetic Basin is a hot-bed of rural poverty in South Asia (SA). Encompassing 99% of the area, the four largest riparian countries India, Pakistan, Nepal and Bangladesh have 47% of their geographical area and 44% of the rural population in the IGB. Of the 291 million rural poor people in the four riparian countries, 135 million lived in the IGB in 2000.

Given that 90% of the poor live in rural areas, poverty is still a rural phenomenon in the IGB. The rural poverty, 56%, 39% and 35% respectively, in Bangladesh, Pakistan and in Nepal are significantly higher than urban poverty, which are 36%, 23% and 7%, respectively. In addition, rural poverty of Indian states, Bihar, West Bengal, Uttar Pradesh and Madhya Pradesh, covering the IGB is also significantly high. Since a major part of the population in this region live in rural areas, rural poverty dominates overall poverty. Agriculture is the dominant source of livelihood for a majority of the rural population in IGB. Thus reducing rural poverty through improving agriculture income is a major pathway for reducing poverty in the IGB.

There is adequate evidence of strong linkages of growth in agriculture productivity and reduction in rural poverty. Adequate access to reliable water and quality land resources are crucial for agricultural productivity growth. However, with increasing pressure on limited land resources, enhancing the value of agriculture productivity per unit of water is becoming crucial for rural poverty reduction. But the spatial information of the linkages of poverty and the extent of water productivity is not clearly understood. Such knowledge is valuable for designing appropriate and geographically targeted interventions for increasing water productivity and thereby reducing rural poverty.

Degradation of natural resources could also be a major constraint for agriculture productivity growth. Punjab and Haryana, the states which lie completely within the IGB, have highly productive irrigated agriculture and one of lowest incidence of poverty. However, intensification of agriculture has resulted in degradation of natural resources in these states. Groundwater exploitation is very high in the western IGB, particularly in Punjab and in Haryana. Water-logging and salinity are threatening agriculture in some parts. To what extent these inhibit the growth of agriculture productivity and poverty alleviation is not adequately understood. Such information is vital for designing adaptation strategies, especially in light of the vulnerability of regions to impacts of the climate change.

There is increasing evidence of climate change causing a gradual depletion of the Himalayan glaciers (*refer* Chapter 3), a major source of renewable water resources in the IGB. Depleting glaciers could have profound effect on the seasonal and spatial water availability in the IGB. Given these changes, it is extremely important to understand the changing dynamics of the nexus of water, land and poverty in the IGB, and how they evolve in the future.

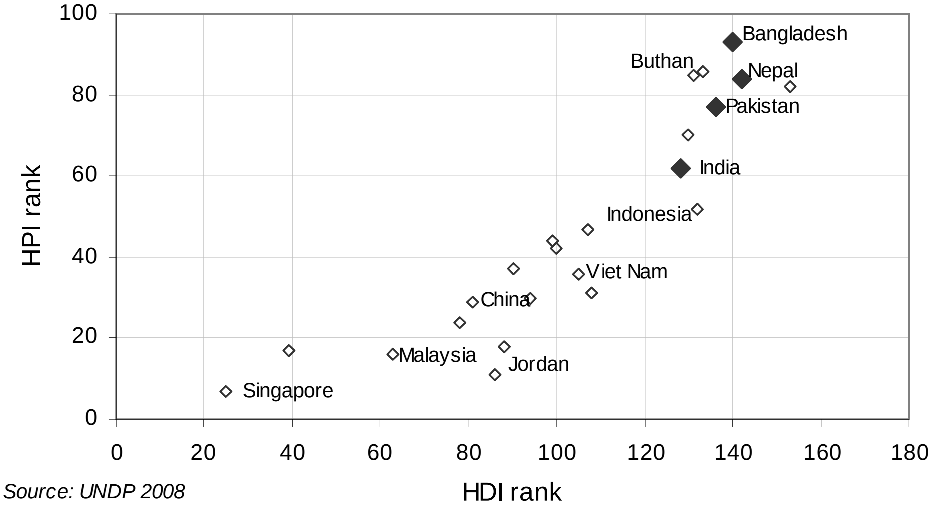
Water is only one component of the agriculture, and the rural livelihoods that depend on it. Hence, unraveling the 'Nexus of Water and Rural Poverty (NWRP)' requires a look beyond an assessment of linkages of poverty with only water related factors. The role of availability and access to water in poverty alleviation depends largely on the influence of agriculture on rural livelihoods. Agriculture has a little influence on the household livelihoods where members are regular or self-employed in the non-farm sector. A clean water supply for domestic purposes is important for this group, particularly for maintaining good health. However, agriculture plays a major role in the livelihoods of agricultural operators and labourers and those who are employed in agri-business related income activities. For them, availability and access to blue water (surface water or groundwater) in the form of irrigation and green water in the form of soil moisture are critical. However, the level of influence again depends on other important parameters for agriculture productivity growth, including access to land in the form of tenure and size; influence of environmental factors such as water logging, soil salinity, water quality; access to infrastructure such as roads, markets and electricity; and socio-economic profile of rural households, including education, social status, and gender.

7.2. Spatial and Temporal Variation of Poverty

Poverty in IGB is multifaceted. Trends of various dimensions of poverty describe the progress of human development; access to basic needs such as water, food, nutrition; extent of livelihood opportunities and income; education, communication, information etc; and access to other infrastructure such as roads, markets, and electricity.

7.2.1. Trends of poverty in the IGB

7.2.1.1. Human Development Index (HDI) and Human Poverty Index (HPI): Low ranking of the Human Development Index (HDI) of the four riparian countries shows the plight of the progress of health, education and economic growth in this region. Among the four countries, Nepal is ranked the last in HDI (142nd in the world), and India is ranked the highest (128th in the world), yet the respective HDIs fall far below most other Asian countries at present (Figure 7.1, X axis).



Source: UNDP 2008

Figure 7.1. Human Development Index (HDI) and Human Poverty Index(HPI) rankings of few selected Asian countries.

The Human Poverty Index (HPI) primarily captures three aspects of the human deprivations; inadequate opportunities for survival (not surviving up to age of 40), for gaining knowledge (adult literacy ratio) and for decent standard of living (un-weighted average of the population without access to safe water and percentage of underweight children). The overall HPI rankings of the four countries are also some of the lowest among the Asian countries (Figure 7.1).

7.2.1.2. Head Count Ratio (HCR): HCR of the riparian countries of IGB has significant improvement lately (Figure 7.2). In India, income of more than half the population was below the poverty line before mid 1970s. HCR has decreased since then, to about 36% by 1993, and 26% by 2000. About 21% of the Indian population lives below the poverty line in 2006. Over this period, the incidence of poverty has declined in both rural and urban areas. Yet, due to large rural population, poverty in India is as much a rural phenomenon today as it was in the 1970's. By halving the rural poverty alone, India could reduce the overall poverty level to single digits.

In Pakistan, the HCR has in fact increased in the latter part of the 1990's, but has declined thereafter. About 22% of the population in Pakistan was poor in 2005. In Nepal and Bangladesh, about 31 and 40% of the population were poor in 2003 and 2005, respectively. In spite of these gains, the poverty associated with high rural population is a major concern in all four countries. For example, 193 out of the 260 million poor people in India live in rural areas. A major reduction in rural poverty will have a significant impact in reducing the overall poverty in these countries.

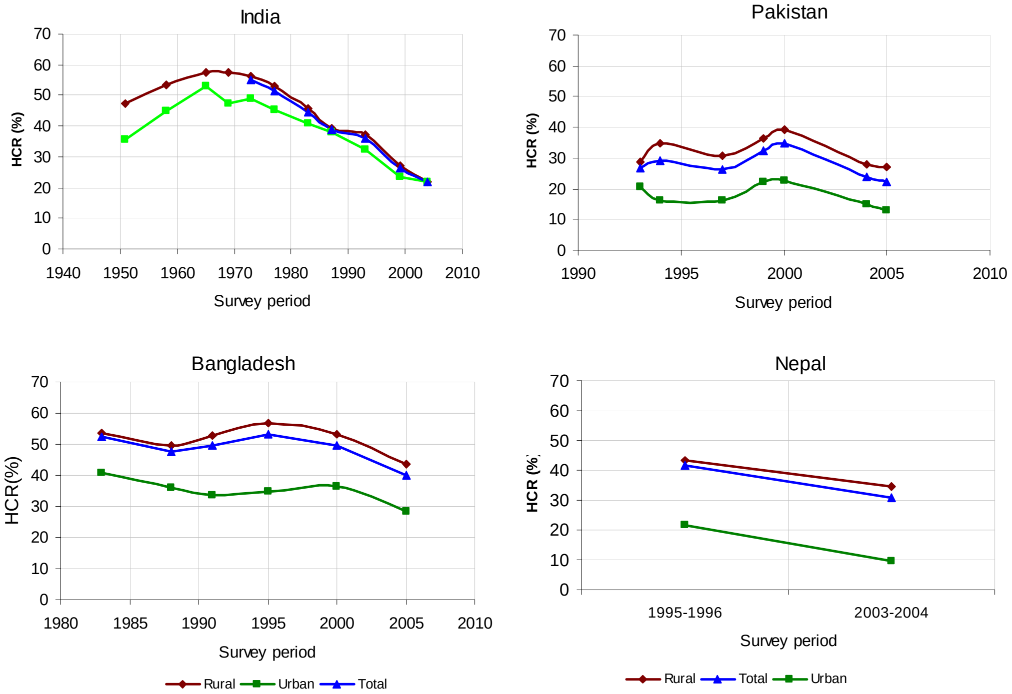


Figure 7. 2. Rural, urban and total head count ratio of India, Pakistan, Bangladesh and Nepal.
Sources:

- i. *Poverty estimates of India from 1951 to 1969-70 are from Dutt (1999), for 1973-74, 1977-78, 1983, 1987-88, 1993-94; 1990-2000 are from the Planning Commission cited in Sharma, 2004. Source for 2004-05 data are from Planning Commission, 2007.*
- ii. *Poverty estimates of Bangladesh for 1983-84, 1988-89, 1990-91, 1995-96, and 2000 are from Bangladesh Bureau of Statistics (BBS,2002) and for 2002 are from BBS (2005).*
- iii. *Poverty estimates of Pakistan are from Federal Bureau of Statistics (FBS) 2001 cited in ADB (2002).*
- iv. *Poverty estimates of Nepal in 1995-96 and 2003-04 are from Central Bureau of Statistics 2005.*

7.2.1.3. Poverty Gap Index (PGI) and Squared Poverty Gap Index (SPGI): The depth and severity of poverty in all demographic groups in the four riparian countries have declined over the last decade. Pakistan still has a significantly high PGI and SPGI, indicating that income of a large part of the poor population is still well below the poverty line, which has a high likelihood of being in chronic poverty in the near-term (Table 7.1). Whereas, the severity of poverty in Bangladesh and Nepal are comparatively lower, indicating a smaller inequities of the income of the poor.

Table 7.1. Poverty gap and square poverty gap in India, Pakistan, Bangladesh and Nepal.

Year	India[1]			Pakistan[2]			Bangladesh[3]			Nepal[4]		
	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total	Rural	Urban	Total
Poverty gap (%)												
1991-1996	5.6	1.4	4.8	7.1	4.3	6.3	7.6	4.3	6.4	12.1	6.5	11.8
1996-2002	3.1	1.8	2.9	4.4	3.3	4.6	8.0	4.6	7.0	-	-	-
2003-2005	3.3	0.3	2.7	6.8	4.6	2.9	5.6	2.9	4.8	8.5	2.2	7.6
Squared poverty gap (%)												
1991-1996	2.8	2.8	-	17.2	12.0	17.2	2.0	1.3	2.4	4.8	2.7	4.7
2000	2.5	1.6	-	12.8	9.1	12.8	2.1	1.4	2.4	-	-	-
2005	-	-	-	9.0	6.5	9.0	1.5	0.8	1.8	3.1	0.7	2.7

Sources: [1]*India data in the three periods refers to 1993-94 (Datt 1998), 1999-2000 and 2005 (Planning Commission 2007).*
[2]*Pakistan data refers to 1998-99, 2001-2002 and 2004-2005, World Bank (2006).*
[3]*Bangladesh data refers to 1998-99, 2001-2002 and 2004-2005, are from BBS 2005 cited in GoB 2007.*

[4] *Nepal data refers to 1995-96 and 2003-04 (CBS 2005).*

7.2.2. Poverty mapping in the IGB

Poverty is a heterogeneous phenomenon, and due to many factors, the extent, depth and severity vary between regions or administrative units or river basins. Information on various aspects of poverty at sub-national scales is presented as poverty maps.

7.2.2.1. Poverty Maps Using National Surveys: These maps show large variations of poverty across the IGB. The HCR is relatively lower in north and north-western parts of IGB (Figure 7.3), which mainly includes northern part of Pakistan and Indian Punjab, parts of Rajasthan in the Indus basin and Haryana and the western parts of Uttar Pradesh of India, and Kathmandu region in Nepal in the Ganga basin. The low HCR regions in India and Pakistan parts of the IGB are known to have high agriculture productivity and growth. And the poverty, especially in rural areas, in these regions was reduced much faster than the other regions. In Nepal, low poverty regions are concentrated in urban centers. The HCR is high in the southern and eastern parts of IGB, consisting of states of Bihar, Chattisgarh, Jharkand, and eastern part of Uttar Pradesh, and Madhya Pradesh in India; southern Punjab, North West Frontier (NWFP), Sindh, and Baluchistan provinces in Pakistan; south-west divisions of Bangladesh; and all NLSS regions except Kathmandu in Nepal.

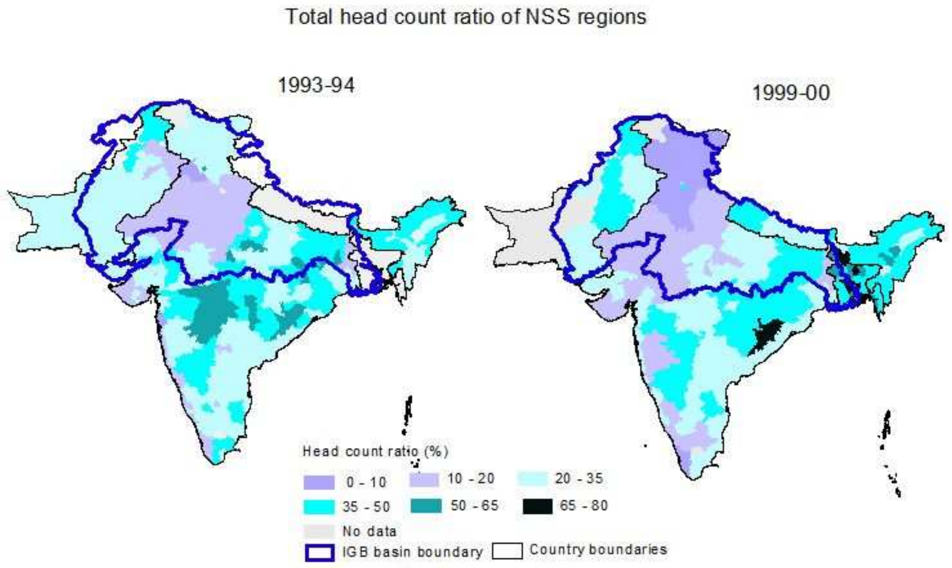


Figure 7.3. Poverty maps across National Sample Survey (NSS) regions in India, districts in Pakistan, and *Zilas* in Bangladesh. (*Source: Deaton 2003, BBS 2003).*

7.2.2.2.The HCR in the Indian part of the IGB in 2004-05: The HCR reveals a declining trend of rural poverty in the Indian IBG (Table 7.2), although large spatial variation is still a pervasive problem (Figure 7.4). In particular, the HCR has decreased from 29.4% in 1999/2000 (National Sample Survey of 55th round) to 24.4% in 2004/2005 (National Sample Survey of 61st round)[7]. On an average, 2.4 million people overcame poverty annually between 1999/00 and 2004/05, notwithstanding that over 78 million rural people still remain poor in the Indian part of the IGB. Spatially, western IGB area presents lower poverty, where the major states such as Punjab, Haryana, Himachal Pradesh and Jammu and Kashmir have some of the lowest HCR at the national level. The HCR is highest in Jharkhand, Bihar, Madhya Pradesh and Uttar Pradesh, which are located in the southern and eastern part of IGB.

---

[7] National Sample Survey organization (NSSO) experiment with data collection methods for increasing its accuracy. Recalled period of collecting non-food data is the main change in recent rounds. Estimates based on mixed recalled period, that the estimates of this paper are based on, are thought to be comparable between the two survey rounds (Planning Commission 2006).

The spatial variation of poverty across districts, presented in Figure 7.4 shows that spatial clustering is prominently visible as the geographic unit becomes smaller. In 2004/05, the rural HCR of districts varied between 0 to 80%. Many of the rural poverty hotspots, i.e. those on the 3rd and 4th quartile of the HCR distribution, are clustered in the eastern IGB (Table 7.2). Bihar and Jharkhand have more than 90% of their poor population in districts in the 3rd and 4th poverty quartiles. A major part of the poor districts of Uttar Pradesh and Madhya Pradesh states are also located in the east and south-east, and more than 80% of the poor population resides in these districts.

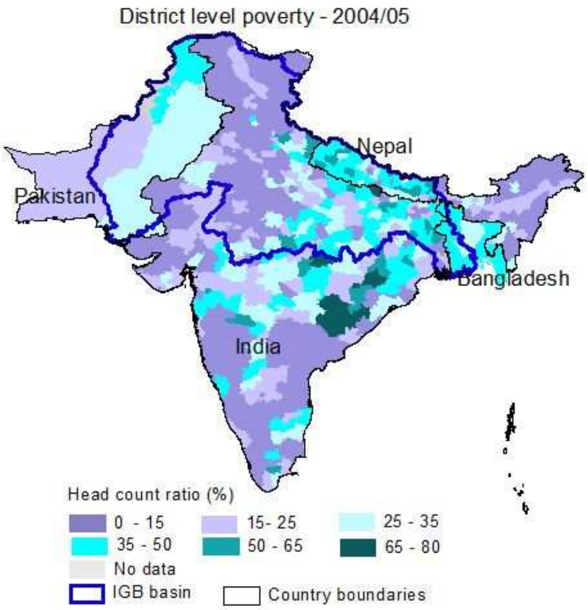


Figure 7.4. Spatial variation of HCR in Indus-Gangetic basin.

Table 7.2. Poverty indicators in the Indian part of Indo-Gangetic Basin.

States in the IGB	Number of districts	Rural poverty indicators (%)					
		2004/05 (61st round)			1999/00 (55th round)		
		HCR	PGI	SPGI	HCR	PGI	SPGI
Jharkhand	13	43.7	11.3	5.3	56.2	11.7	3.6
Bihar	37	33.6	7.5	2.9	42.3	8.3	2.4
Uttaranchal	13	33.3	7.2	3.0	31.7	2.3	0.5
Madhya Pradesh	35	29.5	8.2	5.6	30.1	6.0	1.8
Uttar Pradesh	70	25.3	6.2	3.2	31.7	6.0	1.7
Chhattisgarh	7	24.5	6.5	5.7	51.6	11.2	3.4
West Bengal	14	24.4	5.4	2.4	29.6	5.4	1.4
Rajasthan	27	11.9	2.4	0.9	13.4	2.0	0.5
Gujarat	1	11.7	1.4	0.2	1.3	0.1	0.0
Haryana	19	9.1	1.9	0.8	7.4	1.3	0.4
Chandigarh	1	7.5	2.0	0.5	7.7	1.6	0.4
Himachal Pradesh	12	7.2	1.2	0.4	7.9	1.1	0.2
Punjab	17	5.9	0.9	0.3	6.0	0.8	0.2
Jammu &Kashmir	9	2.8	0.4	0.1	3.9	0.5	0.1
Delhi	5	0.0	0.0	0.0	0.7	0.0	0.0
IGB	280	24.4	5.8	2.9	29.4	5.6	1.6

Source: Author's estimates based on NSSO data of the 55th and 61st round

7.3. Water- Land- Poverty Nexus (NWLP)

Pressure on the natural resource base is high throughout the IGB. Water and land use patterns vary significantly from up-stream to downstream locations, and also changed vastly over the last few decades (CPWF 2003). Poverty is low in up-stream locations while it is high in the down-stream. Understanding the causes and effects of water and land use on low poverty in the upstream, let alone unravelling the nexus in the whole IG basin, requires careful analyses of spatial information.

Figure 7.5 is a schematic representation of water- land - poverty nexus in rural areas. Poverty is a cause and effect of many factors. Thus the focus of this analysis is to extract the contribution of agriculture for rural livelihoods and poverty alleviation, and then how availability and access to water and land influence this contribution.

If agriculture economic activities, whether direct or indirect, are not a major part of income generation of a households or a community, then focus on availability of and access to water and land for agriculture hardly make any difference. We identify locations in the IGB that offer scope for agriculture growth. Our hypothesis is *that agriculture growth will result in significant decline in the incidence of rural poverty in many parts of the IGB*. In addition, when extensive input application such as fertilizer and irrigation causes land degradation, agriculture can be a constraint for reducing poverty, and in some instances a cause for increasing poverty. The extent and the magnitude of the water-land-poverty nexus, as shown in Figure 7.5, depends on how these factors interact with many other demographic, socio-economic, hydro-meteorological, environmental, and policy and institutional factors.

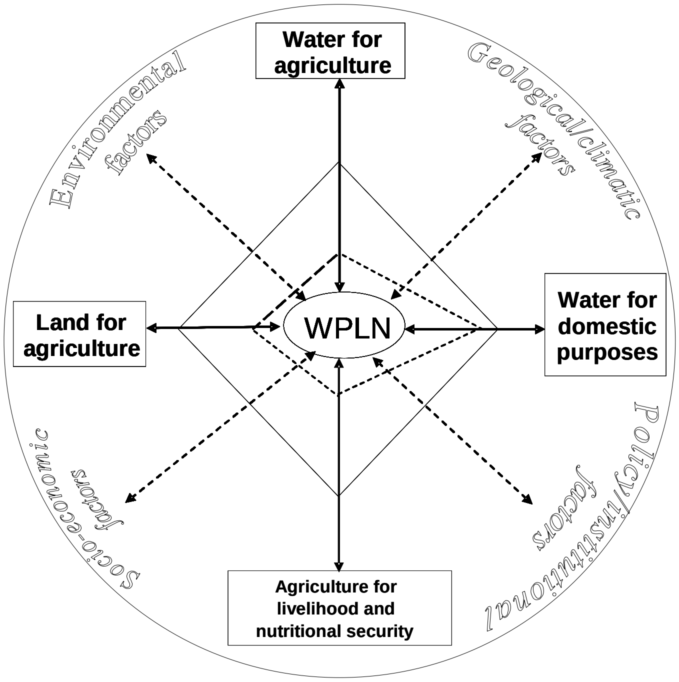


Figure 7.5. Framework for understanding water-land-poverty nexus (NWLP).

7.3.1. Linkages of agriculture growth and poverty

Agriculture sector contributes to about 20% of the GDP in India, Bangladesh and Pakistan. Yet, due to large population base, livelihoods of many of the rural poor still depend on agriculture. Such livelihood patterns are more prevalent in the IGB region and agriculture sector still contributes to a significant part of the regional GDP.

Among the poorest Indian states in the IGB, the agriculture sector in Bihar contributes to 39% of the total GDP. And in Uttar Pradesh and West Bengal, it contributes to 34 and 28%, respectively. In the well-off states of Punjab and Haryana, agriculture contributes to 30 and 37% respectively, but the value generated per unit of land is much higher here. There still are large opportunities for reducing rural poverty in the IGB through agriculture growth (Figure 7.6(a) and (b)).

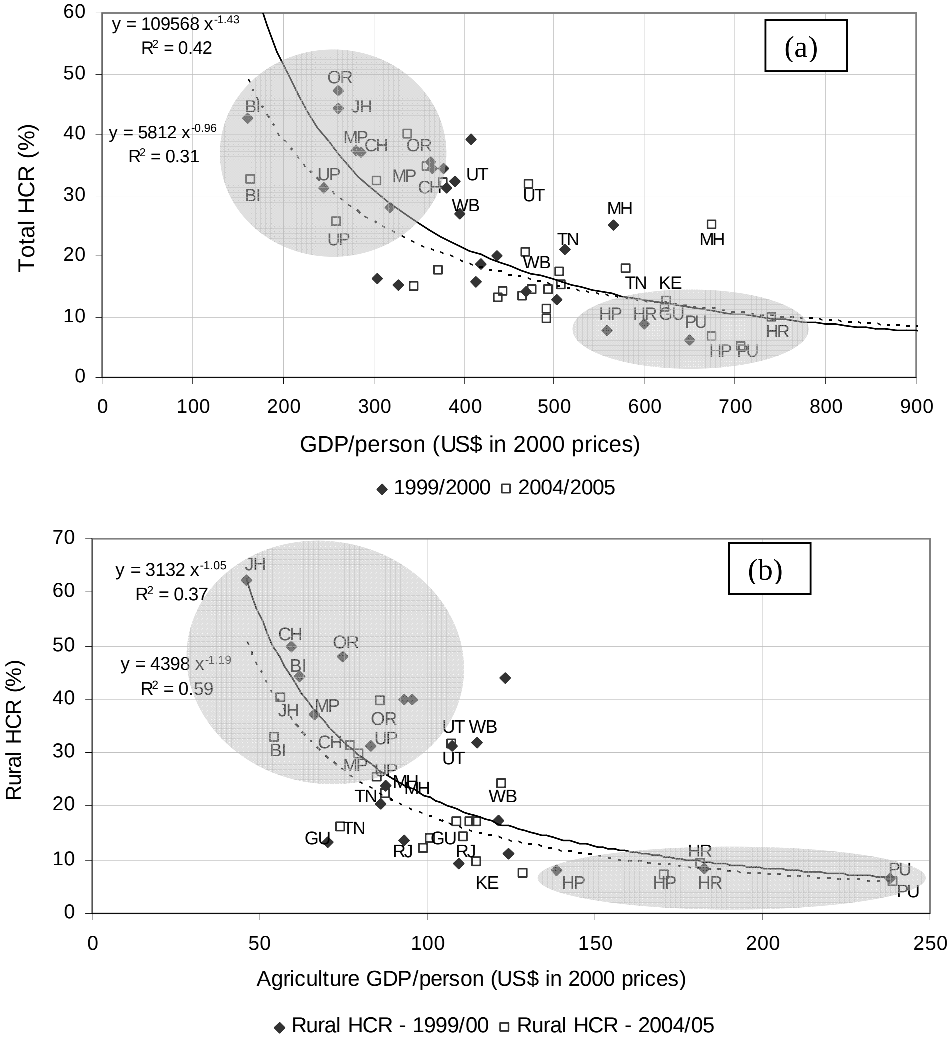


Figure 7.6. Change in (a) per capita GDP and (b) per capita agriculture GDP (constant 2000 $) with total head count ratio in Indian states.
Keys: **BI- Bihar**, CH-Chattisgarh, GU- Gujarat, **HP- Himachal Pradesh**, **HR- Haryana**, MH – Maharashtra, **MP – Madya Pradesh**, OP – Orissa, **PU- Punjab**, **UP – Uttar Pradesh, UT – Uttaranchal, WB – West Bengal,**(States in bold are part of the IG basin)

Data across Indian states in 1990/2000 shows that, on average, 1% increase in GDP/person can decrease total HCR by 1.4% (solid trend line of HCR versus GDP in Figure 7.6(a). In fact, overall economic growth has contributed to substantial poverty reduction in many of the poor states covering the IGB. This includes Bihar, Jharkhand, Chhattisgarh, Uttar Pradesh, Madhya Pradesh in the group in the top left hand corner. A major part of the overall poverty reduction in these states was due to growth in agriculture GDP. A 1% increase in agriculture GDP shall reduce rural HCR by about 1% (solid trend line of HCR versus Agriculture GDP in Figure 7.6(b).

However, there are some exceptions. Per capita agriculture GDP of Bihar has not increased between 2000 and 2005, but the rural HCR has decreased by about 10 percentage points. Many other non-farm factors, including migrant labor to other states and countries, should have contributed to this change. But rural poverty is still high in Bihar (33%), and given its large rural agriculture population, rapid growth in the agriculture sector could reduce rural poverty much faster. Growth in well-to-do states in the IGB, such as Punjab and Haryana has virtually no growth in agriculture GDP/person, thus had virtually no reduction in rural poverty. Exception to this is Himachal Pradesh, where policy induced crop diversification from basic cereals to horticulture is contributing to increase in agriculture GDP and reduce poverty. In Haryana and Punjab, growth in non-agriculture sector economies has contributed to a major part of the overall poverty reduction. Reducing rural poverty in these states may require different approaches.

Diversification to high value crops as in Himachal Pradesh, or expansion of non-farm sector and employment in rural areas shall be the way forward. The elasticity of poverty and income across states based on 2004/05 data show that 1% increase in overall GDP and agriculture GDP should contribute to a reduction of 0.96 and 1.19% reduction of total and rural poverty. Thus, there is a large scope for reducing rural poverty through agriculture growth. That in turn can have a large impact on reducing overall poverty in these states.

7.3.2. Linkages of water and poverty

Access to irrigation, especially through groundwater gives a greater control of water supply. A reliable irrigation supply is a key determinant for better inputs use, such as improved seed varieties, fertilizer, pesticide etc. They increase productivity and income and reduce poverty. This is clearly the case in Punjab in Indus and Haryana in Ganga basin (Figure 7.7.), where irrigation, much of that through groundwater, covers a large part of crop land. These two states have some of the lowest rural poverty. Similar situation exists in western Uttar Pradesh, although the poverty estimate at the state level hides the spatial variability. However, there are some exceptions. Although not as high as in western parts of the IGB, the access to irrigation in eastern IGB, comprising Bihar, eastern parts of Uttar Pradesh and in western Bangladesh is substantially high, but poverty is also high there. Low productivity due to recurrent floods, and inadequate infrastructure facilities, such as roads, markets, electricity, are major constraints in this area. Access to irrigation is low in West Bengal and northern Madhya Pradesh, and a large part of the rural population depends on rainfed agriculture. Recurrent droughts are a major constrain for high productivity there.

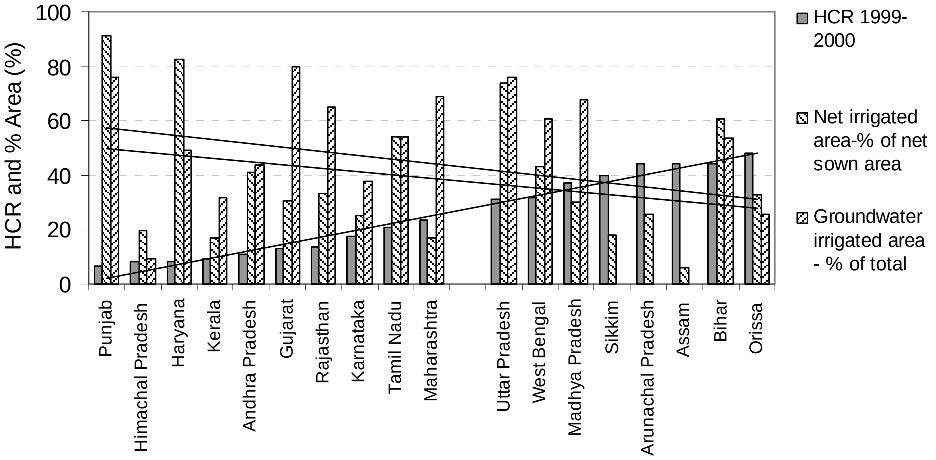


Figure 7.7. Head count ratio in rural areas versus net irrigated and groundwater-irrigated area. (*Sources: GOI 2005).*

7.3.3. Linkages of land and poverty

While, the incidence of poverty among the marginal to small land-holders in central and eastern IGB states (Bihar, West Bengal, Uttar Pradesh, Madhya Pradesh) is very high, it is not strikingly lower among the large land holders in these states (Figure 7.8). In comparison, poverty among the medium to large landholders in the states of western IGB is almost non-existent.

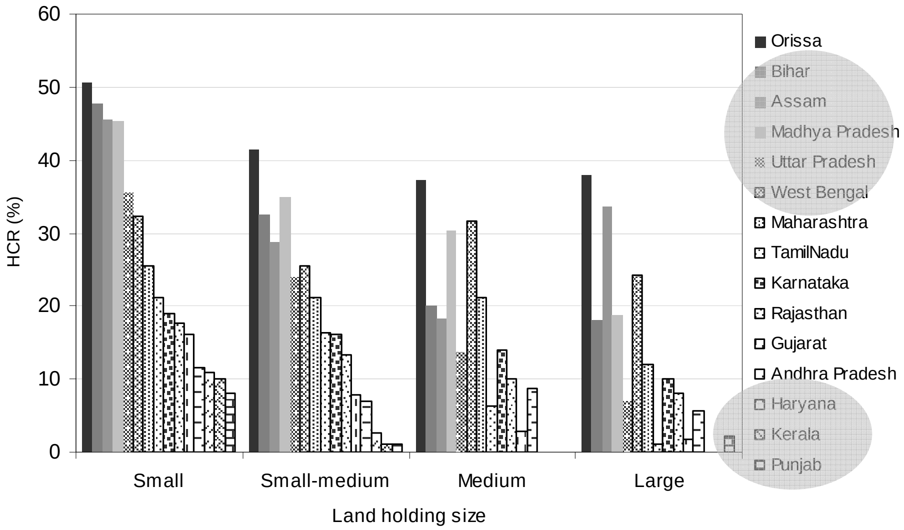


Figure 7.8. Rural head count ratio across land holding classes in Indian states. (*Sources: Panda (2003). (*Notes: Land-holding sizes (in ha) in India are marginal to small (0-1), small-medium (1-2), medium (2-4), large (4 and above)

Poverty among the landless in Pakistan and Bangladesh is even worse. In Bangladesh, more than 50% of the landless people are poor, and the poverty among the small land holders are three-times higher than the large land holders (GBD, 2006). Reduction of poverty among the landless was very slow in Bangladesh, where 61% of the landless rural population was poor in 1988/89 (Ravallion and Sen, 1994), and this has only decreased to 53% by 2000; and to 49% by 2005 (GBD 2006). The incidence of poverty in the near landless (0-0.5ha) and marginal land holders (0.5-1.5ha), 48 and 33%, are more than twice the poverty levels of small (1.5-2.5 acres) and marginal (2.5-7.5 acres) land holders, respectively. Moreover, rural poverty in Bangladesh is high in lowland and upland areas (Kam et al 2005). Indeed, land ownership, holding-size and land quality aspects are significantly associated with rural poverty in Bangladesh.

In Pakistan, more than half of the landless population, whose livelihood depends on agriculture, is poor (Anwar et al 2004). Skewed land ownership, where two-thirds of the population has no access to land and another 18% with small agriculture land holdings (<5 acres), is a major determinant of poverty in Pakistan. However, in Nepal, more than half the population in landless to small land holders is poor, but poverty among the large land-holders is not strikingly lower (Chhetry, 2007; Pant and Raj, 2008). Low land productivity is a major factor that separates the rural poor from non-poor in Nepal.

Although access to irrigated land, is a major determinant of decreasing rural poverty, intensive irrigation could also contribute to land degradation and threaten the very benefits that irrigation has delivered to the rural people. Degraded lands in turn contribute to low productivity and profitability. There are also evidences of high incidences of poverty among those who use wasteland for agriculture.

7.3.4. Linkages of water for domestic purposes and poverty

There is evidence that lack of access to safe drinking water and sanitation, another dimension of human deprivations, is an effect of poverty (Abeywardane and Hussain, 2002). Inadequate access to safe domestic water supply affects health, mainly of the poor. At times, women and children spend substantial time in securing drinking water supply from faraway places. All these could cause or lead to potential economic losses. Over 299 million people or 31% of the rural population in the IGB countries lack access to safe drinking water supply (UNDP 2008). And over 796 million or 84% of the rural population lack access to safe sanitation facilities. However, their linkages with incidence of poverty, somehow, are not exactly clear with the available spatially aggregated information (Figure 7.9).

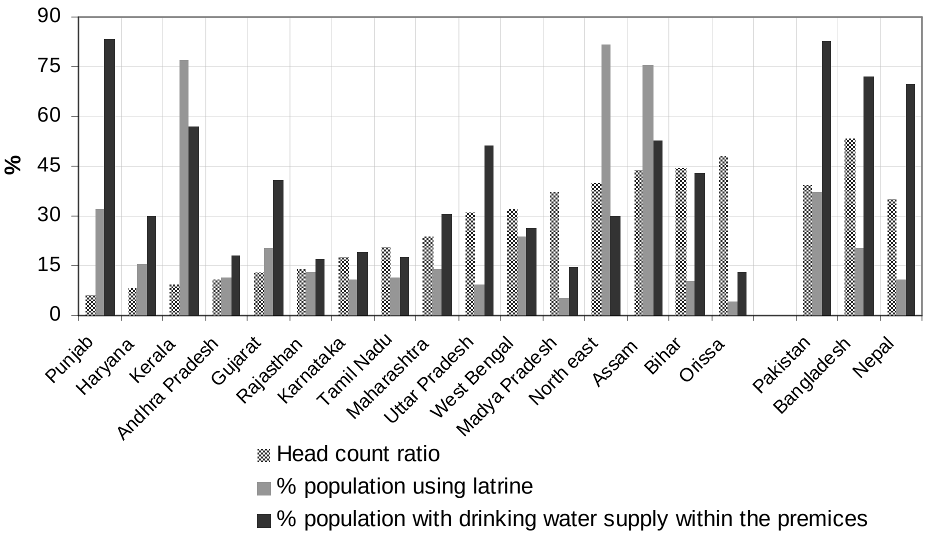


Figure 7.9. HCR and per cent population with drinking water supply in the premises and using toilet facilities. (*Sources: Indian data are from IndiaStat.com 2008. Pakistan, Bangladesh and Nepal data are from UNDP 2008).*

7.4. Water-Land-Poverty Nexus (NWLP) Analysis at the Household and District Level

This part of the analysis used a Logit Regression (LR) model, combining explanatory variables extracted from secondary data on households and administrative units, for understanding NWLP at the household and district level. The LR model examines the probability (P) of a person in poverty given the socio-economic status, assets of households, and cropping patterns, crop productivity, land tenure and holdings sizes, water sources and irrigation patterns, and level of infrastructure development of administrative districts.

The P/ (1-P) is called the odds ratio (OR) of a person being poor. The exponential of the coefficients of the LR model gives the odds of a person being poor with respect to the corresponding explanatory variable given all other explanatory variables remaining constant. In the case of continuous explanatory variables, positive (or negative) odds shows that higher (or lower) values of the variables are positively associated with higher poverty. In the case of categorical variable, exp.(coefficient) show the odds of poverty of different categories with respect to a reference category. The value of OR significantly different from 1 shows the strength of positive or negative association with poverty.

The data for this analysis is extracted from the NSSO 61st round survey in 2004/05, which contains 32,230 household records in 280 districts in 16 states or union territories. The parameter estimates are shown in different groups in Table 7.3 to show the linkages of agriculture for rural livelihoods, and access to water, land and infrastructure for agriculture, and other socio-economic factors influencing or influenced by rural poverty. The estimates of the coefficients (B), standard errors (SE) and the odds ratio (OR) of each explanatory variable are shown in column 3, 4 and 5. The OR is the exponential value of coefficient estimate, and shows the odds of a household being in poverty with respect to a given characteristics.

Table 7.3. Parameter estimates, standard errors and odds ratio of the logit regression model.

	Explanatory factors	Household /District	B	SE (B)	OR (B)
	Agriculture for rural livelihoods				
1.	Average food grain yield	DI	-0.26	0.001	0.770
2.	Fruits/Vegetable area - % of GCA	DI	-0.03	0.000	0.970
3.	Household type (non-agriculture work)	HH			
i.	Agriculture labor		0.81	0.002	2.251
ii.	Non-agriculture labor		0.34	0.002	1.410
iii.	Self employed in non-agriculture		-0.07	0.002	0.931
iv.	Agriculture operator		0.10	0.002	1.105
	Water for agriculture				

4.	50% exceedence probability rainfall	DI	-0.52	0.002	0.592
5.	Gross irrigated area (GIA) -% of GCA	DI	-0.01	0.000	0.991
6.	Groundwater irri. Area - % of GIA	DI	-0.01	0.000	0.993
7.	Groundwater irri. area *50% prob. Rain	DI	0.004	0.000	1.004
8.	Water productivity of irri. food grains (WPIFG)	DI	-0.60	0.010	0.547
9.	WPIFG * % gross irri. area	DI	-0.001	0.000	0.999
10.	Irrigated area - % of cultivable area	HH	-0.26	0.001	0.770
	Land for agriculture				
11.	Marginal & small land holdings-% of total (PCTMSLH)	DI	0.97	0.005	2.649
12.	Cultivable area per person	HH	-0.38	0.005	0.681
13.	Land holding type (large)	HH			
	i. No land		0.94	0.013	2.561
	ii. Marginal		0.69	0.013	1.994
	iii. Small		0.12	0.012	1.130
	iv. Semi medium		-0.30	0.012	0.736
	v. Medium		-0.37	0.012	0.689
14.	WPIFG*PCTMSLH	DI	0.710	0.010	2.034
	Infrastructure for agriculture				
15.	Road density	DI	-.01	.000	0.991
16.	Percent of households with electricity for lighting	DI	-.004	.000	0.996
17.	No access to electricity in the household	HH	0.64	.001	1.905
	Other Socio-economic factors				
18.	Male headed household	HH	-0.62	.001	0.533
19.	Dependency Ratio	HH	0.01	.000	1.016
20.	Social status (Others)	HH			
	i. Scheduled Tribe (SCT)		0.72	.002	2.071
	ii. Scheduled Class (SCC)		0.44	.001	1.559
	iii. Other backward classes (OBC)		0.06	.001	1.065
21.	Religion (Hindu)	HH			
	i. Muslim		0.13	.001	1.144
	ii. Other non-Hindu		0.41	.003	1.517
22.	Education of household head (graduate)	HH			
	i. No education none		0.21	0.004	1.239
	ii. Primary		0.23	0.004	1.268
	iii. Secondary		-0.16	0.004	0.850
23.	Number of graduate/post graduates	HH	-0.44	0.002	0.639
24.	Household size (>=7)	HH			
	i. Size=6		3.93	.003	51.14
	ii. Size=5		3.44	.003	31.19
	iii. Size=4		2.92	.003	18.57
	iv. Size=3		2.43	.003	11.36
	v. Size=2		2.05	.003	7.840
	vi. Size=1		0.78	.004	2.190
25.	Dwelling type (Rented)	HH			
	i. Not rented or own		0.26	.005	1.307
	ii. Own		0.29	.005	1.338
26.	Source of cooking (LPG/electricity)	HH			
	i. Other sources		1.01	.004	2.762
	ii. Kerosene		1.15	.004	3.178
27.	Type of ration card (Others)	HH			
	i. Antodaya		0.04	.001	1.045
	ii. BPL		0.31	.001	1.370

7.4.1. Agriculture for rural livelihood

The agriculture related economic activities are still the dominant form of livelihood of the rural population (Figure 7.10). Agriculture operators, although slightly declined in relative terms between 1999 and 2004, are still by far the largest group in the IGB. Poverty is relatively lower in this group, but the sheer magnitude of the poor population dictate that agriculture productivity growth is necessary for reducing poverty further in this group. Reduction of rural poverty can be accelerated in a two-track approach. While the pro-poor agriculture growth interventions can still play a major role in reducing poverty in the agriculture operator households, improving skills and enhancing opportunities for employment in the non-farm sector can reduce poverty among the agriculture laborers.

In the IGB agriculture growth is significantly related to yield growth of food grains, and crop diversification. The existing grain yields range from 0.9 t/ha in the central region in Bihar to 4.5 t/ha in the western Punjab and give a strong indication of the magnitude of the scope for agriculture productivity growth. Districts with high percentage of fruits and vegetables area are significantly associated with low HCR. This indicates that crop diversification can also have a great potential for reducing poverty among the marginal and small land-holding households, of whom the HCR is one of the highest.

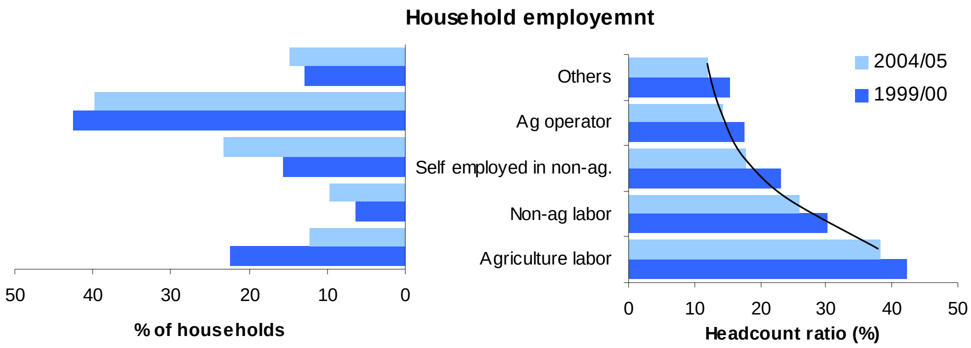


Figure 7.10. Distribution of households and rural headcount ratio according to extent of household's primary employment, and education of the head of the household *(Source: Author's estimates based on NSSO 55th and 61st round).*

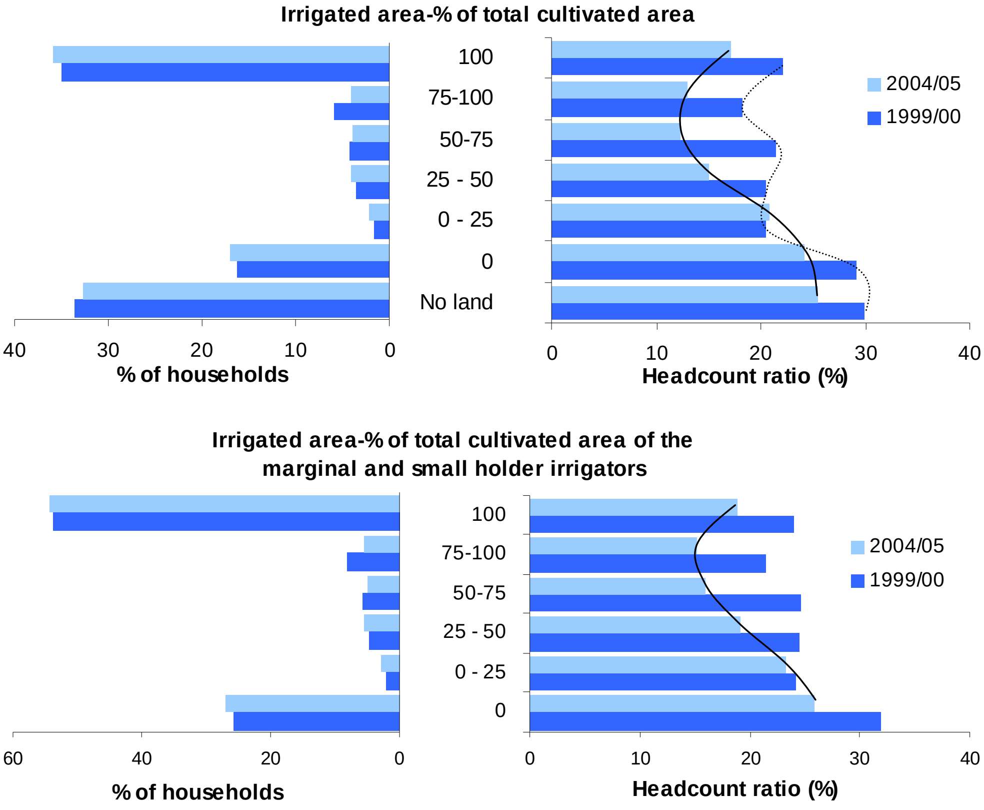
7.4.2. Water for agriculture

LR model shows that rainfall, access to irrigation, groundwater irrigation, and water productivity in irrigated agriculture are all significant in explaining the variation of HCR in the IGB. Within the IGB, households with large irrigated crop area have significantly low poverty. And the districts with large gross irrigated area relative to gross cropped area also have significantly lower incidence of poverty.

Exploring further we find that 63% of the households have access to land, and three-quarter of them have access to irrigation (Figure 7.11(a). The incidence of poverty of the household without land and without irrigation are similar, but decreases with more access to irrigation. However, it also indicates that access to irrigation is not a sufficient condition for reducing poverty of those who irrigate 100% of their land. Such poverty trends are similar among the marginal and small land holders[8] too (Figure 7.11(b), and many of them are located in the eastern IGB.
Higher access to groundwater, in general indicating a reliable irrigation supply, is also associated with low poverty. This mainly captures the low HCR in Punjab, Haryana and Western Uttar Pradesh, where access to groundwater is substantially high. However, the positive coefficient of the interaction term of groundwater and rainfall also shows that access to groundwater is not necessarily positively related in lowering poverty in some regions. The intensity and reliability of rainfall is particularly important for rainfed agriculture dominated areas, where irrigation is the source of water supply for less than 20% of the cropped area. These areas include upper catchments of Himachal Pradesh, Jammu and Kashmir and West Bengal, and the southern regions of the Madhya Pradesh, Rajasthan and in the states of Chhattisgarh and Jharkhand. Positive interaction of water productivity and extent of irrigated area also shows that by increasing access to irrigation and productivity growth can accelerate poverty reduction in low water endowed area.

---

[8] Cultivated area with size 0-1ha, 1-2ha, 2-4ha, 4-10ha, and greater than 10 ha are defined as marginal, small, semi-medium, medium and large land-holdings.


Irrigated area-% of total cultivated area

Irrigated area-% of total cultivated area of the marginal and small holder irrigators

Figure 7.11(a). Distribution of households and rural headcount ratio according to extent of irrigation of the cultivated area, and (b) cultivated area of marginal and small holder irrigators *(Source: Authors estimates based on NSSO 55th and 61st round).*

7.4.3. Land for agriculture

LR model shows that land ownership, land holding size, and large number of marginal and small land holdings are significantly associated with high rural poverty across IGB districts. Among the IGB households, 33% have no access to land. A further 54% have only marginal to small land-holdings. This is a major constraint in the eastern region, where states such as Bihar, Jharkhand and Uttar Pradesh (excluding the western parts) have more than 90% of their land-holdings in marginal or small category, but they contain less than 62% of the net sown area (fig. 7.12). Moreover, many of these small land holdings are highly fragmented and therefore seemed to be a major reason for low inputs and productivity. These areas are the hotbed of rural poverty in the IGB. The LR analysis shows that marginal land-holders, with HCR of 22% in 2004/05, have 2 times higher odd being in poverty in comparison to the large land holders, of whom the HCR is only 4% (Table 3). Districts with large number of marginal and small land- holdings are also associated with significantly high rural HCR.

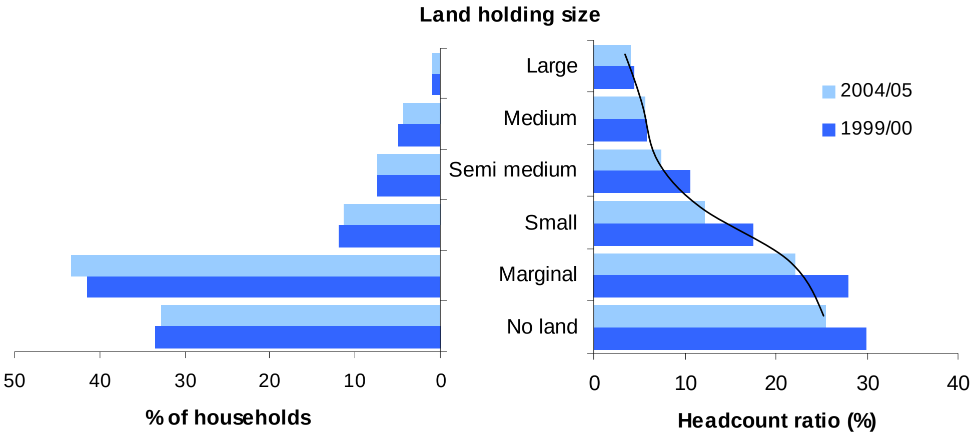


Figure 7.12.. Distribution of households and rural headcount ratio in different land holding sizes in NSSO 55th and 61st round.
(Source: Authors estimates based on NSSO 61st round)

7.4.4. Infrastructure for agriculture

Access to infrastructure such as road, markets and electricity can also have a major influence in reducing poverty. Inadequate access to power supply is a major reason for booming groundwater markets in the eastern IGB. But it is also a major constraint for overcoming poverty for many marginal and small farmers due to high cost. Districts with higher road density are associated with low HCR. As roads and markets are developed more or less simultaneously, we can safely assume that lack of markets is also a main determinant in the regions with high rural poverty.

7.5. Water-Land-Poverty Nexus: Lessons from the Case Studies in India, Pakistan, and Nepal

Case studies were also conducted in IGB countries to examine the NWLP at household level, using questionnaire survey. The survey was based on three separate questionnaire instruments responding to the village and household profile and to fragmented landholding cultivation. In India, survey was conducted in three least progressive districts of Bihar; Vaishali, Darbhanga and Munger. In Pakistan, case study site was Rechna Doab and in Nepal, study was conducted in four villages of Morang and Sunsary districts. Inferences from these case studies are summarized below.

7.5.1. Property rights on status of water resources

The acknowledgement of water as a public good but usually with private implications in the supply stage complicates the property rights scheme. In India (Bihar site), more than two-thirds of the respondents purchase agricultural water from unofficial trade schemes. 68% of the sample purchases water from trading mechanisms while 20% own the water resource and only 6% make use of public water source, which in this case is considered to be supplied by canal irrigation. However, in Pakistan each farmer could individually allocate his own share in the canal network. Thus, the supplies from the traded water are reduced to half while the canal irrigation is increased to sevenfold. In the case of Nepal, the pumping practices are quite rare and the canal water is acknowledged as a public property. Therefore, the public use of canal water almost monopolises the water property status while the ownership condition of a tubewell is minimal in the study villages.

7.5.2. Water volume allocation in property rights schemes

In the Indian case, about two-third of the buyers and the water owners respectively, make exclusive use (100%) of the specific water source without combining any other additional source. However, in the case of canal irrigation, only about 20% of the canal water users solely (100%) depend on the canal supply. The rest of the canal users are almost equally distributed towards a conjunctive use of water sources which is based on a proportion of 20%, 40%, 60% and 80% of canal water accordingly. In the case of Pakistan the situation is quite different. Majority of the tubewell owners cover only a small amount of the entire supplies though this source. Farmers having canal water supplies allocated the water volume among other sources in almost equal quantities, while the exclusive use is rather rare. Half of the water buyers are provided with about 20% of the entire required water through trading while the rest are equally distributed. In case of

Nepal, the amount of water use from each water source is allocated entirely from each dependent source and thus a further analysis is of little value.

7.5.3. Property rights of conjunctive water use

In case of India, the option of water trading in conjunction with the ownership or canal use reaches about 15%. The conjunctive use of tubewell and canal seems to be negligible as well as the case of simultaneous use of all the three source types. However, the situation is not the same in Pakistan where 1/3 of the canal users simultaneously pump water from tubewell sources. Another almost 1/3 canal users are getting supplies through traded water. The case of conjunctive tubewell and trading is much lower than in India while there is no observation of simultaneous use of all the three types of water sources. In case of Nepal there is little conjunctive use of canal and tubewell water (except for very few cases).

7.5.4. Distribution of water source to be traded

This data is available only for Indian case, where tube well water source dominates volumes of traded water while a small amount is derived from canal and pond/tank sources. It should be mentioned however, that the sample refers only to the 48% of the total buyers who stated the origin of the traded water while 52% did not mention the water source. The high dominance of tubewell irrigation in water trading is further clarified through the investigation of the water volume levels to be exchanged through the trading parties. The total water quantity of tubewell trading supplies the entire needs (100%) of the buyers. However, in the case of pond/tanks the explicit dependence on this traded water is decreased to 10% while such a situation is absent in the case of canal water buyers.

7.5.5. Farmers’ perspective towards agricultural water use

7.5.5.1. Farming constraints: In Indian case, the paucity of funds (credit) is claimed to be the major reason of low productivity. This is closely followed by water insufficiency and unpredictable weather conditions. Of lower importance but still in high priority are the low yielding seeds and the low fertiliser application. In turn, average importance is mainly given to the weed infestation, the insufficient machinery and the high prices of the inputs. The salinity, the local infrastructure and the weak access to markets seem to be of the lowest significance for the respondents. In case of Pakistan, the water insufficiency is by far the most significant constraint. Low fertiliser application and the weeds’ infestation are prioritised in much lower ranking. Village infrastructure, low accessibility to markets and the weather conditions stand on the very opposite to the farmers’ perception with the lowest importance. In the Nepal case, only the six prime constraints are prioritised by boosting even higher the water insufficiency factor. Closely below follows the fund paucity factor while the third option resembles to the Pakistan case by adding in the picture malpractices together with insects and diseases as new constraints. Of moderate importance appears to be the poor infrastructure within the village.

7.5.5.2. Farming challenges: In case of India, improved water availability comprises the major factor for yield increase with very high weightage as compared to other options. In a much lower preference, there is the access to credit, the weed control and the accessibility to quality inputs. Of moderate importance are the sufficient machinery and the supplies with lower price of the essential inputs. The potential factors for improving productivity in Pakistan are highly driven by improved water availability. Almost unanimously, the respondents selected the water as the major factor while far below there are the need for low input price, canal rehabilitation and water saving technologies. In the case of Nepal, the importance of water availability is increased even more through a unanimous acceptance of the respondents. Importance is also given to the low input prices and the access to quality inputs as second and third alternative options among the prime priorities.

7.5.5.3. Training requirements: In all the case study sites, respondents gave priority to the introduction to new technologies and specialised training on methods of production improvement. The enhancement in mushroom cultivation and dairy/goatry products appear to be attractive alternative options in Indian case.

7.5.5.4. Micro-credit financing: For the Indian case, the highest percentage responded negatively for such schemes although reluctance to a ‘truthful response’ to the question was recorded by the local researchers. This situation was due to their unwillingness to reveal the informal loans obtained from local money lenders. The compelling factors for such loans were mainly attributed to the support for agricultural operations in a broad manner and in a far less extent to farming support and poultry. In the Pakistan case, only 14% of the respondents availed micro-credit loaning, which is invested in the agricultural operations. In Nepal, half of the respondents depend on micro-credit loaning, which is used for agricultural support, although poultry is also of some importance.

7.5.6. Water and environmental implications

Understanding of the interrelation between the environmental status of the natural resource related to agriculture and the productivity is quite recent in the study areas.
7.5.6.1. Groundwater markets: Primarily, the willingness of the farmers to support groundwater market for the supervision of the water allocation and sustenance of the resource is questioned. In turn, their financial contribution for the establishment of this groundwater market is queried. In the case of India, most of the respondents appear highly willing to set up a groundwater market although a bit lower affirmative response was noticed when the financial contribution is asked. For those who oppose on contributing to such institution, almost half do not have sufficient finances for such an undertaking. Also, one-third of the respondents object the selection of the farmers as the stakeholders to financially support the setting up of the groundwater market. In Pakistan case, the adherents of a groundwater market are almost equal to the arguers. Further, majority of farmers are against the idea of contributing financially to the set-up of the groundwater market. The most in favour of a groundwater market potential appear to be the Nepalese farmers from all of the study villages. Almost unanimous stance for both the establishment of such a market and their willingness to contribute denotes their highly agreeable position.

7.5.6.2. Environmental services: Initially, the acceptance that the water charges do not include the effects to natural environment is acknowledged. Taking this argument into consideration, the farmers are asked whether they would contribute to the preservation of environmental services i.e. conservation of water, anti-erosion effects etc., if asked by governmental bodies. In India, almost 70% of the respondents are willing to contribute to preservation of natural environment. However, the situation is capsized in the case of Pakistan, by presenting the vast majority of the respondents to be unwilling to support a financial contribution for the environmental services. The preferences of the Nepalese farmers are rather close with the Indian case by attributing almost the same results when asked about their contribution. The reasoning of denying the potential contribution to such an undertaking is their inability to afford an extra burden.

7.5.6.3. Cooperative Tubewell Scheme/ Systems: The sustenance and even regulation of groundwater is questioned through the revitalisation/ introduction of common tubewell systems. In the case of Pakistan and Nepal, the option of revitalising/introducing a common tubewell system was not investigated because of the unfamiliarity of both the areas examined with such practices. In India, 70% of respondents agree to the setting up of common tubewell systems. Also, the potential of discontinuation of irrigation of their farms from any other source than the common tubewell for the sake of sufficiency is investigated. In this case, the willingness to accept (WTA) a reimbursement is questioned as a compensatory mechanism. Surprisingly, for the Indian case the majority of the respondents are not agreeable to such an option.

7.5.6.4. Water consumptive crops: Pakistan and Nepali farmers were asked if they would agree to get reimbursed in case they would be requested to abandon the cultivation of water consumptive crops (e.g. HYV rice). More than 80% of Pakistan farmers disagree to such an option, whereas in Nepal, vast majority of the respondents were agreeable with the potential of abandoning water consumptive crops.

7.5.6.5. Water governance: At first place, the common acceptance of an increased consideration towards the water governance is exhibited. Thereafter, the farmers were asked whether they would desire to get involved in water management issues through an active role. In an almost absolute stance, they believe that this is solely the work for experts or maybe experts and elected representative but not for the farmers. Surprisingly, more than 50% of the total sample respond to the subsequent question regarding the prioritisation of water related issues in case they would acquire an active role. This behaviour may reveal a latent willingness of the farmers to get an active role in water governance but their lack of adequate knowledge may inhibit them from expressing their implicit feelings. The water and crop productivity as well the water and environment constitute the major concerns for the respondents. The irrigation techniques and the pricing appear to present issues of moderate importance. The lowest ranking is mainly attributed to the property rights regime and the water allocation factors. In Pakistan, the major concern for the water related issues appears to be the property rights regime among all the others. In a lower priority are the issues of water and crop productivity while the environmental concern is prioritised in the lowest ranking. Nepali farmers prioritise the water irrigation techniques and the water pricing as the major themes to get involved with and of lower importance stands the water efficiency in terms of accessibility and distribution.

7.6. Conclusions

Some of the important conclusions brought by the synthesis and analysis of the water-land-poverty nexus in the Indo-Gangetic basin include the following:

i. A nexus of water and poverty exists where people are poor, agriculture plays a significant part of the poor livelihoods and water plays a crucial role in their agricultural activities. This indeed is the case in the IGB region of South Asia.

ii. Growth in agriculture output could still have a significant effect in reducing rural poverty in households with access to land. This is especially true in the poverty stricken eastern parts of the IGB. A significant part of the rural households in the IGB also have no access to land and poverty is relatively high there. Growth in non-farm sector employment opportunities and income seems to have significant effect in reducing poverty for this group. Thus, growth in overall gross domestic product (GDP) can significantly influence poverty alleviation in rural areas.

iii. Access to a reliable water supply is a key component of agriculture growth and rural poverty reduction in the IGB. Water availability is low in the western IGB, but access to irrigation, especially to groundwater, was a key component in agriculture growth and poverty reduction there. However, water availability is not a significant constraint in the eastern and south-eastern regions where incidence of poverty is significantly high. Increasing access to groundwater is a major driver for poverty reduction there. However, the high cost, due to abstraction through diesel pumps or purchase from the groundwater market, is a major impediment for adequate access to groundwater. This is further aggravated by marginal or small land holdings. In these areas, access to a reliable electricity supply can make a major impact in increasing access to groundwater irrigation.

iv. Increasing access to groundwater is necessary but not a sufficient condition for reducing poverty among the poor marginal land holders. These land holders should diversify their cropping patterns to high value crops to increase the value of water productivity. Knowledge transfers from east and south-eastern regions in the Asian region on crop/agriculture diversification can be of great help for the poor farmers in the eastern Gangetic basin. Increasing access to roads and markets are also key components to facilitate this growth path.

v. Large number of marginal and small land holdings in the eastern regions is also a major constraint for improving productivity and lowering poverty. The ratio of number of marginal and small land holdings to number of agriculture operators in Bihar and West Bengal are significantly higher. This indicates that many land holdings are fragmented and have substantial number of non-contiguous parcels. Such land holdings are generally found to have inefficient input allocations. Clearly, some smart form of land consolidation is required to make a big impact first on input application and then on water productivity growth and poverty alleviation.

vi. A substantial number of poverty hotspots also exist in locations where rainfed cropping patterns dominate. These include districts in Jharkhand, Chattisgarh and Madhya Pradesh. Access to small but critical supplemental irrigation there can increase input application and hence can have a big impact on crop yields and overall agriculture productivity growth.

vii. Looking through the micro- analysis on the selected case studies of India, Pakistan and Bangladesh, a rather diversified outcome is portrayed. The results on the property rights in regard to water status accentuates the almost sole dependence of Indian farmers to traded water and hence their high vulnerability on non-regulated water markets. The Nepalese farmers seem engaged with the canal irrigation supply system while the Pakistani farmers present an ample portfolio of different supply sources and hence less vulnerability to scarcity effects. The water supply issue consist the major constraint and challenging factor for all the three case studies while the funding inadequacy is exhibited as the second most significant one. However, the need for additional funding was not revealed in the loaning related question due to the unwillingness to admit the funding from private money lenders.

viii. The study of water and environment figured an overall rather positive stance of the respondents towards potential water conservation schemes. Indian farmers appeared to be more robust in financially contributing or accepting a reimbursement for water protection except for the case of replacing their own tubewell system with a common source. A negative almost stance towards the willingness to accept an amount for the management of agricultural operations is given by Pakistani farmers which nevertheless are agreeable with the other proposed measures. Finally, the water governance field seem to be a latent but major issue for the respondents if adjudging their interest in participation to the decision making process in specific sectors.

Overall, the macro and micro analysis on the examined areas of Indus and Ganges basins is aspired to attribute a holistic and in depth overview of the current water and poverty nexus.

CHAPTER III

OUTCOME AND IMPACTS

The project had very short duration of two years to conduct research, generate output, produce outcome and create impact. In this context, sharing the generated new knowledge and creating sustainable repository of knowledge is the most important element towards creation of impact of the project. Yet, considering its importance a 'Knowledge Management ' work-package was designed to systematically acquire, process and disseminate data, information and new knowledge generated in the project. The next chapter briefly describes the knowledge management and impact strategy of the project.

8. KNOWLEDGE MANAGEMENT AND IMPACT OF THE BFP INDO-GANGES

Mir Abdul Matin, Bharat R Sharma

8.1. Introduction

It is important to disseminate findings and recommendations from various work packages of the BFP-IGB across the basin to NARS and other stakeholders in the basin countries. The project had relatively short duration (2 years) to complete the process of designing and implementing the research, generate output, produce outcome and create impact. The 'Knowledge Management and Impact' package was designed to systematically acquire, process and disseminate data, information and new knowledge generated during the project. These efforts firstly support other work packages in collecting and collating the data required for analysis and secondly to use various channels to disseminate the new information/ databases and knowledge. Knowledge management activities under the projects are described in Table 8.1.

Table 8.1. Knowledge management activities under the BFP-IGB project.

	Component	Function
i.	Data management	Data acquisition, collation of spatial data, prepare metadata
ii.	Access to existing knowledge	Knowledge harvesting, sharing
iii.	Knowledge development	Investigation, analysis, synthesis
iv.	Application	Informed decision making
v.	Knowledge dissemination	Publication, communication, and knowledge portal development

8.2. End Users and Beneficiaries

The ultimate beneficiaries aimed by the projects are the people in the basin to improve their livelihood through better management of water resources for agricultural production and livelihoods. But there are formal and informal stakeholders in between with different roles to help the process from generation of findings to uptake by the target beneficiaries for maximizing the positive impact. Table 8.2 shows various beneficiaries of the project and what would be the possible impact on these stakeholders.

8.3. Impact Pathway

Challenge Program on Water and Food (CPWF) and the CPWF Basin Focal Projects (BFPs) adopted an impact pathway approach where each of the projects would develop its own impact pathway to facilitate evaluation of project outcome and its impact on the targeted beneficiaries. Impact path way framework developed for the Basin Focal Project is shown in Figure 8.1.

To ensure that the project could deliver quality outputs and anticipated impacts take place in the basin, it is important to identify various agents/ actors of change. These agents are grouped into four categories: sponsors, partners, and scaling-up and scaling-out agents. It is also important to analyze relative importance of each agent and their attitude toward the expected changes. Impact pathway networks for each of the four IGB countries were prepared through discussion with stakeholders during the inception workshop held in Dhaka (Bangladesh) in February 2008. These networks identified various agencies and their role and attitude to plan for action to strengthen positive and minimize negative attitudes of different agents. The impact pathway networks for the four riparian countries (India, Pakistan, Nepal and Bangladesh) are shown in Figure 8.2.

Table 8.2. Impact on various beneficiaries of the project

Beneficiary	Type of benefits	Impact
Researchers in the IG basin	Access to quality assessed data New research methods	Consistency and quality of research output
Challenge Program on Water and Food (CPWF)	Easy access to research output and data	Achievement of research objectives and ready access to quality controlled data in phase II of CPWF
National agriculture and water management network	Better understanding of water management issues in the basin and access to relevant knowledge bases	Facilitate informed decision making for better water management and improved productivity
National Agricultural Research Systems(NARS)	Easy access to research outputs and networking with other similar agencies	Improved awareness of water management problems and interventions in the basin.

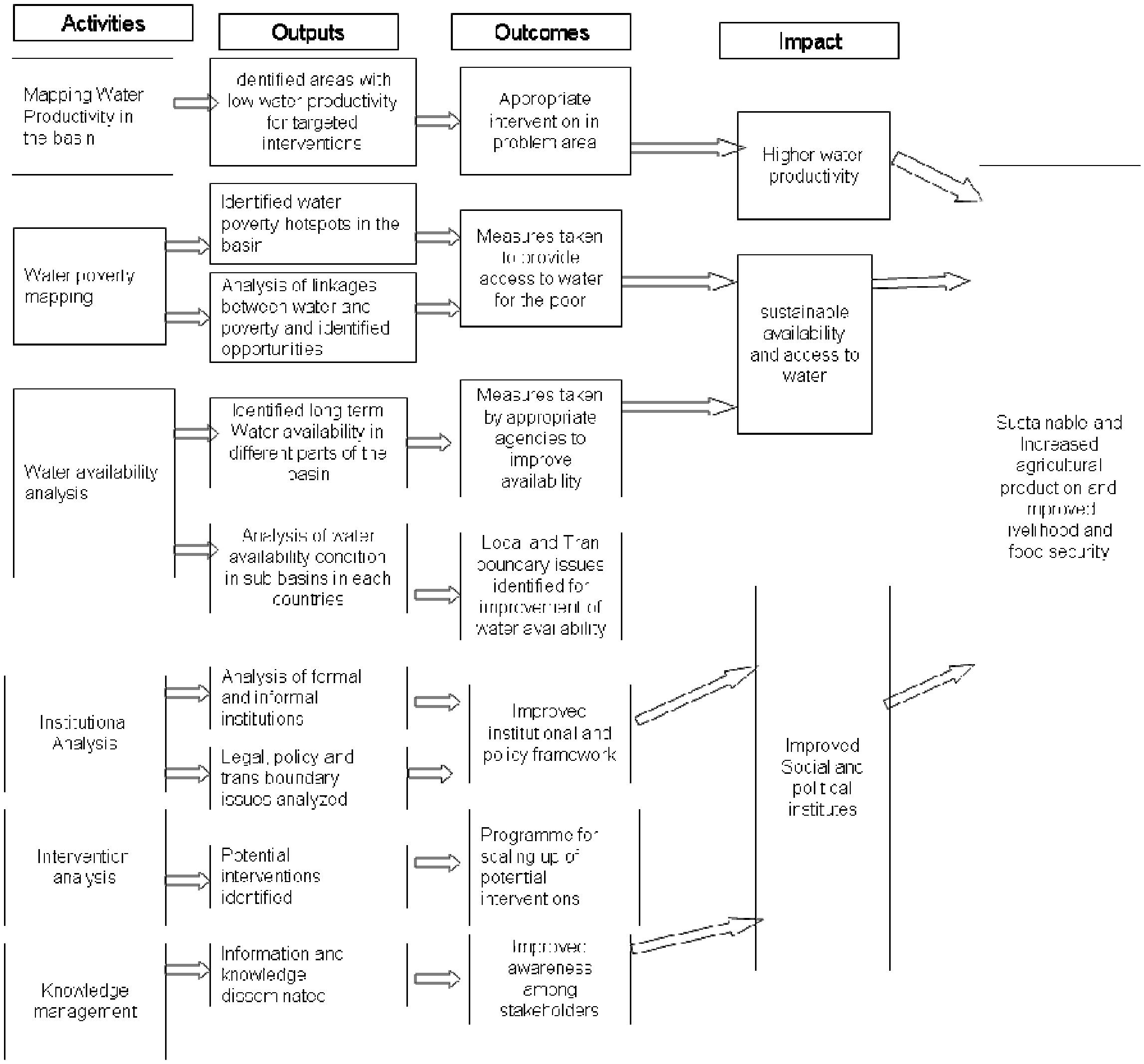


Figure 8.1. Framework for impact pathways for the CPWF Basin Focal Projects

(Source: Douthawaite (2008), Challenge Program on Water and Food)

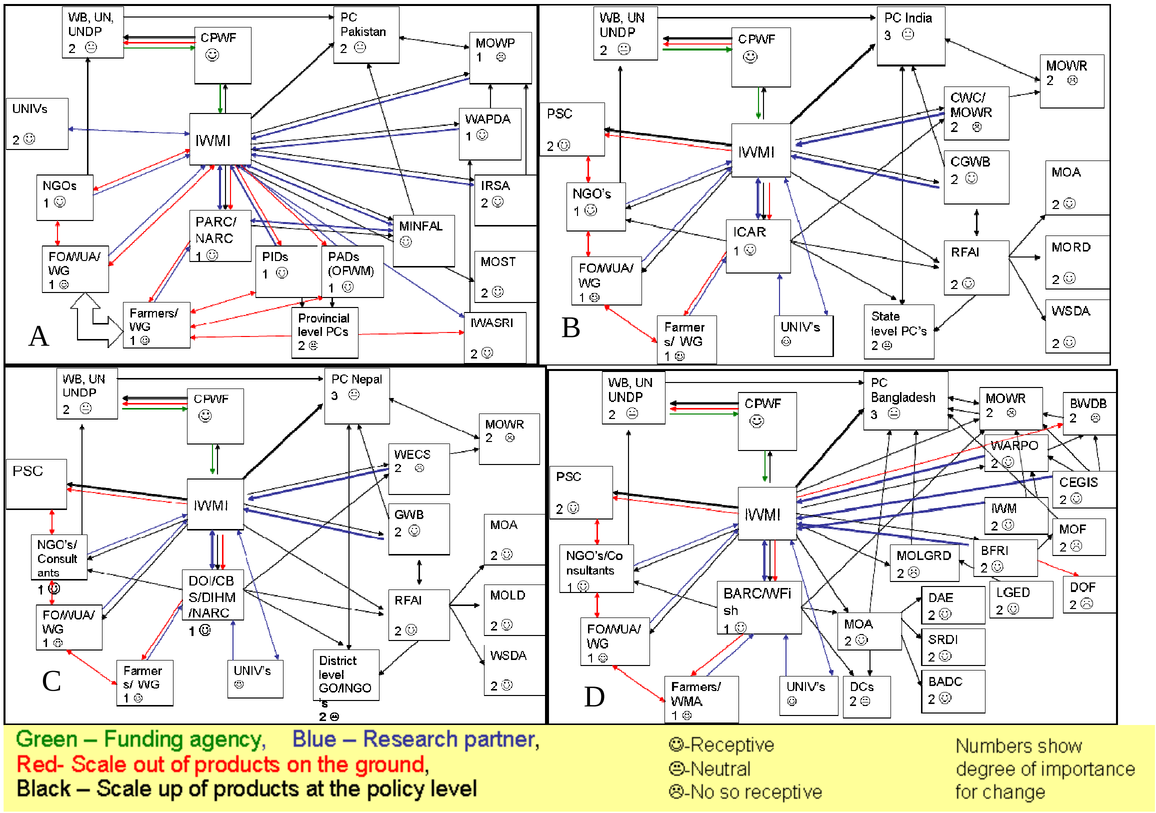


Figure 2: Impact pathway networks for IGB countries (A: Pakistan, B: India, C: Nepal, D: Bangladesh) *(The abbreviations in the networks are explained below)*

Important Abbreviations, (A)Pakistan: IWMI: International Water Management Institute; CPWF: Challenge Program on water & Food; PARC: Pakistan Agricultural Research Council; WAPDA: Water and Power Development Authority; IWASRI: International Waterlogging and Salinity Research Institute; MOWP: Ministry of water and Power; MOST: Ministry of Science & Technology; WB: World Bank; PID: Provincial Irrigation Department; PAD: Provincial Agriculture Department; PC: Planning Commission

(B):India: ICAR: Indian Council of Agricultural research; CWC: Central Water Commission; MOWR: Ministry of Water Resources; CGWB: Central Ground Water Board; MOA: Ministry of Agriculture; MORD: Ministry of Rural Development; WSDA: Watershed Development Agency; RFAI: Rainfed Area Authority of India

(C): Nepal: WECS: Water and Energy Commission Secretariat; GWB: Ground Water Board; MOLD: Ministry of Land Development; NARC: Nepal Agriculture Research Council

(D): Bangladesh: BARC: Bangladesh Agriculture Research Council; WFish: WorldFish Centre; BFRI: Bangladesh Fishries research Institute; CEGIS: Centre for Environment and Geographic Information System; BADC: Bangladesh Agriculture Development Corporation; MOF: Ministry of Fisheries; DAE: Department of Agriculture Extension; WARPO: Water Resources Planning Organization

A summary description of the Project Impact pathways is given in Table 8.3

Table 8.3. Summary description of the BFP-IGB project's main impact pathways.

Actor or actors who have changed at least partly due to project activities	What is their change in practice? i.e., what are they now doing differently?	What are the changes in knowledge, attitude and skills that helped bring this change about?	What were the project strategies that contributed to the change? What research outputs were involved?	Please quantify the change(s) as far as possible
Scientists/ Researchers	i.Access to quality assessed data. ii. New methodology for basin –level water productivity mapping	i.Comprehensive data set for the basin. ii. RS-GIS-census integrated system for WP assessment	i.Web-based IDIS Data sharing system. ii. Capacity of the partners in the new methodology	i.IDIS is an online data sharing system with over 1 billion records, with focus on CPWF basins. ii. Similar methodology is now used for the Chinese basins
National agriculture and water management network	Informed decision making for better water management e.g. delayed transplanting of paddy to reduce GW overdraft in Punjab	Better understanding of water management issues in the basin and access to relevant knowledge bases	A well-articulated dissemination strategy and effective engagement with policy-planners.	Upto 7% of real water savings through lesser groundwater pumpage in the water stressed areas of Punjab.
National agricultural research systems	Improved awareness of water management problems and interventions in the basin.	-Role of RCTs especially laser land levelling in water savings. - improved culture and capture fisheries in Bangladesh sub-basin.	Easy access to research outputs through project website and networking with other similar agencies	The project website (http://bfp-indogangetic.iwmi.org:8080/) provide a one stop access to all project outputs including research reports, project reports, workshop presentations, data and maps.
Policy makers	More attention to the specific issues on water resources in IG basin	-Highlighting the water-energy nexus for poor farmers of the Ganges basin. - Better quantification of the water-land-poverty nexus and its alleviation.	-A set of research briefs based on project findings. -Presentations made to the top-level policy planners. -Effective and wider coverage in the media.	-Six research briefs based on findings from all work packages were prepared and distributed to policymakers from IG basin countries. -Blogs and media coverage reached to a vast number of people.

Of the changes listed above, which have the greatest potential to be adopted and have impact? What might the potential be on the ultimate beneficiaries?

i. The data and basin-wide information collected under the IDIS has a great potential to be used by a number of researchers and analysts working in the region and elsewhere.
ii. The new methodology of regional/ basin-wide water productivity estimation and precise identification of the 'bright spots' and 'hot spots' of water productivity has a great potential for its wide scale adoption.

iii. The ultimate beneficiaries (poor and small holding farmers with low productivity) shall be benefitted through better targeting of the development programs aimed at at livelihood improvement.
iv. Access to water resources is likely to be improved through better designed water development programs in the basin.

What still needs to be done to achieve this potential? Are measures in place (e.g., a new project, on-going commitments) to achieve this potential? Please describe what will happen when the project ends.

This project has developed a comprehensive database and a detailed analysis of the resources, water productivity, poverty and resource governance in the basin. It has also identified a set of important interventions which will potentially improve the productivity and thus improve the livelihoods of the rural population. However, given the short duration and resources, it has not been able to directly work with the communities to assess the impact of potential interventions. The CPWF has plans to launch a more specific Project for the more vulnerable areas of the Ganges basin. It shall be much helpful for launching this project at the earliest opportunity so as to gain from the comprehensive knowledge, partnerships and networks developed during the project.

Each row of the table above is an impact pathway describing how the project contributed to outcomes in a particular actor or actors.
Which of these impact pathways were unexpected (compared to expectations at the beginning of the project?)

i.The project researchers received a request from the Chinese academies to impart the knowledge on the new methodology of Basin Level water Productivity Assessment. This was not expected from the BFP-Indo-Gangetic Basin.
ii. Studies on Multiple-Use water Systems in Nepal Hills attracted the attention of research and development departments working in the poor and tribal regions of north-eastern Himalayan region.

Why were they unexpected? How was the project able to take advantage of them?

These were unexpected mainly because these actors and agencies were much outside the basin boundaries and the project did not make any special effort to reach them. The project took advantage of these opportunities by working closely with them and improving their professional capacity through more targeted activities.

What would you do differently next time to better achieve outcomes (i.e. changes in stakeholder knowledge, attitudes, skills and practice)?

The project shall like to organize few more focused and specialized programs for improving the capacity of stakeholders in some advanced technologies, e.g., use of RS-GIS in regional water productivity mapping, use of WEAP modeling for estimating the impact of snow/ glacier melt in the Himalayas.

The project shall like to work closely at least with some selected on-going development programs to assess the impact of potential interventions for livelihood improvement and enhancement of productivity.

Work more closely with major donors in the region to showcase the potential threats and opportunities so as to leverage better attention and reality based development programs in the basin.

8.4. Data Management and Database Development

Scarcity of good quality data for water resources (especially at the river basin scale) and agriculture research is a significant problem in IG basin. One of the objectives of this work package was to provide quality controlled data to project researchers to ensure quality of research outputs. A systematic data acquisition, processing, management and archiving procedure has been implemented in the project.

Assessment of data needs for different work packages and researchers was done at the beginning of the project. Table 8.3 shows different data and their relevance to each of the work packages. Based on this an inventory of available data among partners was prepared that helped in identification of data gaps. Respective national partners were instrumental to identify possible data sources in respective countries. Data were collected from several sources including public data portal, NARS, National data providers and individual researchers and primary data collection through detailed surveys. Before using these data for analysis, most of the data were validated and converted to standard formats consistently across the project. A data sharing system was developed within Integrated Data Information System, IDIS (IWMI and CPWF data portal) to facilitate sharing data among researchers within the project period. Alternatively, researchers shared data by other means including e-mail, DVDs, FTP. All the researchers were encouraged to share data to avoid duplication of effort for data collection and processing.

Besides secondary data, ground truth data were collected to support analysis of satellite image for water productivity mapping. Ground truth (GT) data covering a large area in India were collected on cropping pattern, water, yield, and socio-economic conditions. Point specific land and water productivity values with physical and social constraint/contribution factors helped to assess the variations, understand causes, and identify appropriate interventions. Ground truth data were collected through land cover samples, questionnaire survey and biomass yield samples. Figure 8.3 shows coverage of ground truth data in India.

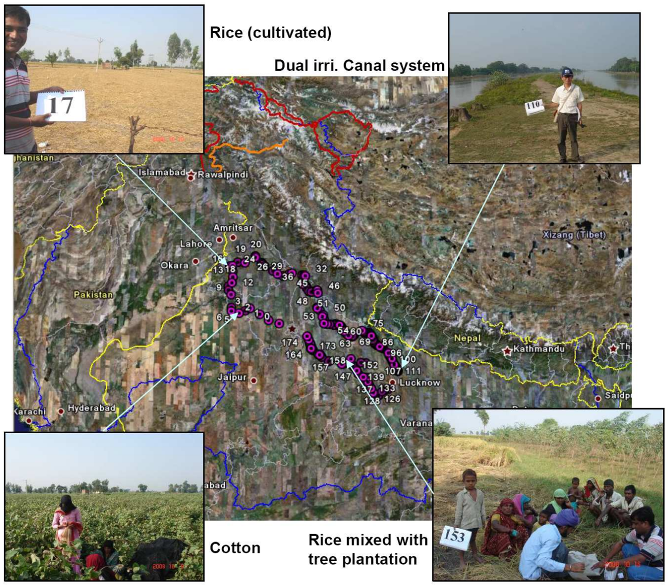


Figure 8.3. Ground-truthing to support satellite image analysis for the IG basin.

For institutional and intervention analysis a large volume of literature were collected on legal, policy, technology and interventions. These documents will be shared for future use considering their copyright status through the project web portal. For water poverty analysis, a large amount of primary data was collected through well-structured village and household level surveys in the representative sub-basins of the IGB. These included villages in the Rechna-Doab sub-basin in Indus-Pakistan; four disadvantaged districts in the Ganga basin (Bihar) in India, Koshi sub-basin in Nepal terai and villages specializing in culture and capture fisheries in the Madumati-Gorai sub-basin in Bangladesh.

Project aimed to archive all the data collected for future use as per CPWF requirements and guideline. Metadata are being prepared using IDIS standard to document all the dataset.

Table 8.4. Different type of data requirement for analysis under the work-packages of the project.

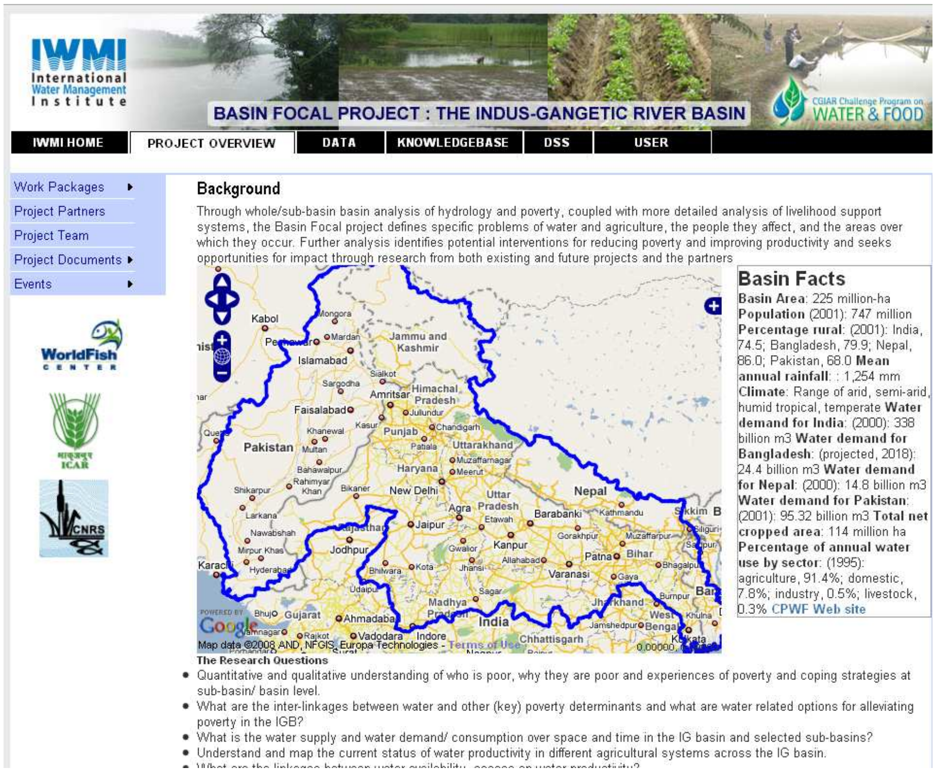
		Work packages					
Category	Description	1. Water poverty analysis	2. Analysis of water availability and access	3. Analysis of agricultural water productivity	4. Institutional analysis	5. Intervention analysis	6. Development and application of the knowledge base
Socio economic	High resolution sub national poverty info Inter sectoral use of water Population census Agricultural census Income and expenditure survey National sample survey	X					X
Climate	Rainfall, temperature, humidity, wind speed and direction, Evapo-Transpiration Location of climatic stations		X	X			X
Hydrology - Surface water	Time series stream flow Stream network Basin and sub-basin boundaries Locatiion of hydrological stations Location of water bodies Location and alignment of water infrastructures		X	X	X		X
Hydrology-Ground water	Time series ground water table Ground water acquifer map Ground water contours Ground water withdrawal Ground water decline		X	X	X		X
Environment	E-flow requirement		X	X			X
Agriculture	Time series data on yield and input (crop, livestock, fisheries) Price/valuation statistics Livelihood data Land use and Land cover Cropping pattern Cropped area (irrigated, rainfed ..) soil Agro ecological zone Irrigation by sources Energy sources for irrigation			X			X
Satellite images	LandSAT MODIS		X	X			X
Documents	Global literature on institutional interventions project documents, government statistics, policies, laws, literature on informatl institutes	X			X	X	X
Base GIS layers	Administrative boundaries Infrastructurs Topography Transportation network Growth centers Urban and rural areas	X	X	X	X	X	X

8.5. Research Products

The project web site is planned to be the knowledge gateway for agricultural water management in IG basin. The primary objective of the site is to provide a one stop access to all project outputs including research reports, project reports, workshop presentations, data and maps. The project documents have been uploaded at:

http://bfp-indogangetic.iwmi.org:8080/aboutBFP/project_document_workshop.php
The site also provides links to similar knowledge products to create a knowledge repository on water and agriculture management in the IG basin.

To promote wider circulation of project outputs, these are also uploaded into CPWF (http://www.waterandfood.org/) website and other knowledge gateways including Bludocs, and a special BFPwiki sites (http://cpwfbfp.pbworks.com/). Similarly, the project web site also provides links to those sites. The web site will facilitate access and exploration of knowledge based on issues, categories and locations. The web site (Figure 8.4) is hosted with basic project information and provides facilities to upload new information into the searchable repository.



Background

Through whole/sub-basin basin analysis of hydrology and poverty, coupled with more detailed analysis of livelihood support systems, the Basin Focal project defines specific problems of water and agriculture, the people they affect, and the areas over which they occur. Further analysis identifies potential interventions for reducing poverty and improving productivity and seeks opportunities for impact through research from both existing and future projects and the partners

Basin Facts

Basin Area: 225 million-ha **Population** (2001): 747 million **Percentage rural**: (2001): India, 74.5; Bangladesh, 79.9; Nepal, 86.0; Pakistan, 68.0 **Mean annual rainfall**: : 1,254 mm **Climate**: Range of arid, semi-arid, humid tropical, temperate **Water demand for India**: (2000): 338 billion m3 **Water demand for Bangladesh**: (projected, 2018): 24.4 billion m3 **Water demand for Nepal**: (2000): 14.8 billion m3 **Water demand for Pakistan**: (2001): 95.32 billion m3 **Total net cropped area**: 114 million ha **Percentage of annual water use by sector**: (1995): agriculture, 91.4%; domestic, 7.8%; industry, 0.5%; livestock, 0.3% CPWF Web site

The Research Questions

- Quantitative and qualitative understanding of who is poor, why they are poor and experiences of poverty and coping strategies at sub-basin/ basin level.
- What are the inter-linkages between water and other (key) poverty determinants and what are water related options for alleviating poverty in the IGB?
- What is the water supply and water demand/ consumption over space and time in the IG basin and selected sub-basins?
- Understand and map the current status of water productivity in different agricultural systems across the IG basin.

Figure 8.4. Snapshot of website developed for Basin Focal Project- Indus Gangetic basin (http://bfp-indogangetic.iwmi.org:8080/)

8.6. Dissemination and Impact Creation

To achieve the targeted dissemination of the most important findings and recommendations of the Project to the researchers and senior level policy managers, specialized workshops were organized and important of these include the following:

i. The Challenges and Opportunities in the Indus-Gangetic Basin (Project Inception Workshop); March 2008 at Bangladesh Agriculture Research Council, Dhaka, Bangladesh.
ii. Basin Focal Project for the Indo-Gangetic Basin: Road Covered and the Way Forward (Review Workshop), Surajkund, Haryana, India (February, 2009)
iii. International Workshop on “Tackling Water and Food Crisis in South Asia: Insights from the Indus-Gangetic Basin” (Final Synthesis Workshop), 2-3 December 2009, India Habitat Centre, New Delhi, India
iv. Special Session on “ Future of Irrigation in Asia” during ICID 60th IEC Meeting and 5th Asian Regional Conference, 6-11 December 2009, New Delhi, India

All these workshops and Special sessions were very well organized and attended by the top water and agriculture and development experts and policy makers (as Secretaries to the Union Governments) and donor agencies. Special comprehensive publications and Policy Briefs were released and disseminated on these occasions. Professional media coverage through news and radio coverage and blogs at the important websites were ensured for wider attention and impact. Some of the stories captured on the net included the following:

i. **Impact of glacier melt on Indus and Ganges flows among IGB results** **http://www.waterandfood.org/news-and-events/news-detail.html?tx_ttnews%5Btt_news%5D=248&tx_ttnews%5BbackPid%5D=25&cHash=953f0e75e2**

ii. **We Are Live Blogging From The IWMI International Workshop on Indus-Gangetic Basin Tomorrow!http://www.indiawaterportal.org/blog/sachin-tiwari/8952** http://indiawaterportal.org/iwmi

iii. **Looking beyond the crisis and asking right questions**: http://indiawaterportal.org/blog/sachin-tiwari/8955

iv. **A river dies of thirst**: http://indiawaterportal.org/blog/sachin-tiwari/8956

v. **Water productivity-approaches to understand and improve:** http://indiawaterportal.org/blog/sachin-tiwari/9031

vi. **The future isn't what it used to be!** : http://indiawaterportal.org/blog/sachin-tiwari/8995

vii. **Placing impact at the pinnacle: http://indiawaterportal.org/blog/sachin-tiwari/8987**

viii. **Act Two - Reach Out, Make an Impact! (Workshop Concludes)** http://indiawaterportal.org/blog/sachin-tiwari/9066

ix. **Tackling Water and Food Crisis in South Asia: Insights from the Indus-Gangetic Basin:** http://www.iwmi.cgiar.org/News_Room/Archives/Tackling_Water_Food_Crisis/index.aspx

x. A radio program (15 minutes) on **"Overexploitation of groundwater in Punjab: Problem and the Prospects"** was recorded with ARD German Radio- WDR 5 (Cologne) and broadcast early January,2010 (Journalist: Stefan Mentschel)

8.7. Strategy for the Future

Basin Focal Project for the Indus-Gangetic Basin has completed its tenure but the knowledge sharing dissemination and impact creation shall continue for quite some time to ensure that the important messages reach to the intended stakeholders and find their way into the new research design and implementation and policy formulation. Though this shall happen through several formal and informal channels and mechanisms, some of the specific activities to achieve these objectives shall include the following:

i. Publication of the important research results through high impact peer reviewed scientific journals and research reports. The project has already achieved a great success in this during life time of the project but shall further strengthen these efforts.

ii. Publication of Water Policy Briefs conveying the important messages of the Project in simple, concise and lucid formats.

iii. Compilation, publication and dissemination of a BFP-IGB project synthesis report.

iv. Preparation of a Book chapter on the "Indus-Gangetic Basin" for the proposed international publication on the BFPs.

v. Preparation of a Journal Article for the Special Edition of an International Journal.

vi. Presentation of the important results, findings and recommendations at the important national and international platforms (Conferences, policy dialogues, donor meetings)

vii. Engage the national researchers/ institutions for capacity building on the new research methodologies and techniques.

viii. Develop future research projects to build on the available knowledge and address problems of productivity and livelihood improvements in the hot spots of the basin.

ix. More seriously engage the donors to design the projects/ development schemes for proper targeting of the R&D investments in the basin.

8.8. International Public Goods

The followings items of significance were developed as International Public goods and have been widely disseminated by use of the interested stakeholders in the basin and beyond:

i. **Water Poverty Maps**: The project developed high-resolution poverty maps for Indus-Gangetic basin countries (India, Pakistan, Bangladesh and Nepal) which very well establish the water-land-poverty linkages and their drivers in these countries. These maps are shown in section 7 (Water-Land- Poverty Nexus in the IG Basin) of the Report.

ii. **New Methodology and Estimation of Basin-Level Water Productivity**: An innovative approach was developed by combining meteorological data, ground survey, and national census with remotely sensed imagery to assess rice and wheat water consumption (actual ET), rice and wheat productivity, and finally crop WP in IG basin. Statistical data were synthesized to calculate district-/state-level land productivity, which is then further extrapolated to pixel-level values using a MODIS NDVI image, based on a crop dominance map. The actual ET is estimated with an SSEB model taking meteorological data and MODIS land surface temperature products as inputs. Water productivity maps are then generated by dividing the crop productivity maps by ET maps. The high quality basin level land and water productivity maps are generated for the first time. These maps further help to identify and quantify the 'bright spots' and 'hot spots' of water productivity in the basin.

iii. **Climate Change Impact on Glacier Melt**: The project has developed and employed for the first time a sub-routine of the WEAP model to estimate the impact of climate change (temperature increase) on the glacier and ice melt and the runoff at the important gauging stations in the Indus and Ganges rivers. The project has developed scenarios under the SWAT models for estimating the impact of land use changes and water infrastructure development on the river flows.

iv. **Water Governance Laws**: The project has made a comparative analysis of the evolution and effectiveness of water resources governanace laws in the IG basin countries and the special role of groundwater governance laws. This compilation shall be available for wider usage by the researchers and water laws practitioners.

v. **Analytical Hierarchy Process Ranking for the Potential Interventions:** The project was able to provide a prioritized ranking to a very huge database of the potential interventions and then provide a set of three most important interventions for the major crops of the basin. Effective implementation of these interventions shall significantly improve the agricultural productivity in the basin.

vi. **Fisheries Water Productivity:** In partnership with the researchers from the WorldFish Centre, Bangladesh, the project has been able to develop a framework and also estimate the water productivity of major fisheries production systems (both capture and culture fisheries) in Bangladesh. The project has also identified the potential threats for fisheries productivity and interventions for fisheries improvement for the individual and community based fish capture and fish farming.

vii. **A project website** (http://bfp-indogangetic.iwmi.org:8080/) is developed to act as a platform for knowledge dissemination. The web site will facilitate access and exploration of knowledge based on issues, categories and locations.

viii. **Comprehensive database:** A large and well collated database on all the important physical, policy, governance and livelihood characteristics of the regions in the Indus-Gangetic basin has been developed and uploaded through CPWF/IWMI portal of the Integrated Data Information system. This is highly useful for conducting further research and policy analysis for improving productivity and alleviating poverty in the basin countries.

ix. **Publications:** A number of project related publications (journal papers, conference proceedings, project reports and research briefs), as given in section 11.

8.9. Partnership Achievements

Partnership in the CPWF lead Basin Focal Projects program helped to secure very effective partnerships with the leading researchers/ research organizations leading to the development of very high quality science. The following outcomes and impacts deserve specific mention:

i. Partnership with **Stockholm Environment Institute (US Centre**) lead to the development of a special sub-routine under the WEAP model which is able to estimate the contribution of snow/ glacier melt to the river flows. It has further helped to estimate the impact of climate change (temperature rise) on the glacier and ice melt and stream flow changes in the river (specific case of the Indus and the Ganges).

ii. Partnership with the **WorldFish Centre, Dhaka, Bangladesh** helped the Project to develop a framework and methodology for the estimation of fisheries water productivity under different capture and culture fisheries systems. This is a new thematic area and a good contribution has been made to the understanding and develo0ment of science.

iii. Partnership with **Indian Institute of Technology, Kharagpur** helped to adapt the Analytical Hierarchy Process (AHP) ranking for prioritization of the potential interventions for improving agricultural productivity in the basin.

iv. Researchers at the **International Water Management Institute** made major contributions through (a) development of an innovative and highly exciting methodology for estimation of regional/ basin level water productivity with capability of pixel-level quantification. The methodology integrated the databases and scientific methods of climate, production census, remote sensing and GIS; (b) developed a framework for the analysis of water-land-poverty nexus and factors contributing to it in the IG basin countries.

8.10. Recommendations

The research and other activities under the Basin Focal Project for the Indo-Gangetic Basin project lead to the following major recommendations:

i. High population growth is a significant driver of depleting and degrading natural resources. Head Count Ratio (HCR) has improved significantly in the recent years; yet, income of a large part of the poor population is still well below the poverty line. Increasing access to and water productivity of irrigation can contribute to poverty alleviation among the small landholders, enhancing access to education and opportunities in non-farm employment are major pathways of reducing poverty among the landless.

ii. Groundwater is the dominant water source and under threat in the IG basin. Rapid agriculture expansion and subsequent utilization of available water resources of the basin has placed the basin at risk with water scarcity issues on one hand, and flooding problems on the other, the scales of which are further exacerbated by impacts of climate change. Further development of the water resources must keep these issues in view to ensure the hydrological sustainability of intensive agricultural systems in the Indus basin and improvement of crop and fish productivity in the Ganges basin.

iii. Water productivity of both rice and wheat is generally low, implying great scope for improvement. General decline in water productivity is observed from Northwest to Southeast. In contrast to the bright spots of well performing areas, for example, Indian Punjab and Haryana, large areas come with extremely poor performance (Bihar and Bangladesh). The variability in water productivity shows no direct relationship with climate conditions, implying the significance of irrigation infrastructure and associated crop and water management. This calls for substantial investments in development of new and rehabilitation of the existing water infrastructure.

iv. IGB is experiencing rising costs of agricultural water use in ways (Energy–water nexus) that have positive water productivity impacts and adverse livelihoods impacts. High surrogate water price is driving out smallholder irrigation. Suitable policies need to be put in place to save the interests of smallholder irrigators which shall lead to increase in productivity and diversification of the agricultural production system.

v. Public irrigation systems grossly under-price irrigation; but these are getting marginalized. despite massive government and donor investments. In the IGB, major challenge is to find ways of bringing down agricultural water use cost below the ‘upper threshold’ beyond which abundantly available water becomes too expensive for the poor.

vi. Adopting Resource Conservation Technologies (RCT) allow farmers to increase area, productivity and intensity of cropping. Delaying the transplanting of paddy to periods of low evapo-transpiration saves precious groundwater and the energy, however the practice needs to consider the entire rice-wheat cropping system. Integrated aquaculture-agriculture and multiple water use systems have great potential in IGB.

vii. Water governance policies, laws and institutions are relatively weak and the existing frameworks/ instruments need adequate strengthening to get the desired impacts of the efficient utilization of the available water resources in the basin**.** Groundwater laws need immediate consideration to ensure its long-term sustainability.

8.11. Publications

(a) Journal Papers

Tushaar Shah, Mehmood Ul Hassan, Muhammad Zubair Khattak, Parth Sarthi Banerjee, O.P. Singh, Saeed Ur Rehman (2009). *Is Irrigation Water Free? A Reality Check in the Indo-Gangetic Basin.* **World Development**. Volume 37, Issue 2, February 2009, Pages 422-434.

M. D. Ahmad, H. Turral and A. Nazeer (2009). *Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan*. **Agricultural Water Management**, Volume 96, Issue 4, April 2009, Pages 551-564.

Christopher. A. Scott and Bharat Sharma. 2009. *Energy supply and expansion of irrigation in the Indus-Ganges basin*. **International Journal of River Basin Management.** Vol 7 (2):119-124.

Asad Sarwar Qureshi, Peter G. McCornick, A. Sarwar and Bharat R. Sharma, 2009. *Challenges and Prospects of Sustainable Groundwater Management in the Indus Basin, Pakistan*. **Water Resources Management**, Springer, Netherlands. DOI 10.1007/s11269-009-9513-3

Cai X L, Sharma B. 2009.*Remote sensing and census based assessment and scope for improvement of rice and wheat water productivity in the Indo-Gangetic Basin*. **Science in China Press/ Springer , Series E-Tech Sci**ence, 52(11):3300-3308

Cai, X.L.; B.R. Sharma. 2010. *Integrating remote sensing, census and weather data for an assessment of rice yield, water consumption and water productivity in the Indo-Gangetic river basin*. **Agricultural Water Management** (Elsevier), 97:309-316.

Ahmad, M.D., H. Turral, A. Nazeer, A. Hussain 2009. *Satellite based assessment of agricultural water consumption, irrigation performance and water productivity in a large irrigation system of Pakistan*. In Thenkabail, P.; Lyon, J.G., Turral, H.; Biradar, C. (Eds.), Remote Sensing of Global Croplands for Food Security. Remote Sensing Applications Series, Taylor and Francis Series in Remote Sensing Applications, CRC Press.

Bharat R Sharma and G K Ambili. *Hydrogeology and Water Resources of Indus-Gangetic Basin: Comparative Analysis of Issues and Opportunities*. Review paper accepted for publication, **Annals of Arid Zone** (India), 41 pages.

(b) Conference papers/Proceedings

Abdul Hakeem Khan, Peter McCornick and Asim Rauf Khan (2008). *Evolution of managing water for agriculture in the Indus River Basin.* Proceedings of the International Forum on Water and Food, (Volume-Ill), Addis Ababa, November 10-14,2008, CPWF, Colombo. Pp 120-123.

Mobin-ud-Din Ahmad and Nilantha Gamage (2008). *Monitoring agricultural water consumption and irrigation performance using freely available MODIS images for a large irrigation system in Pakistan*. Proceedings of the CGIAR Challenge Program on Water and Food, Second International Forum on Water and Food, 10-14 November 2008, Addis Ababa, Ethiopia. (Vol I). Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food: 123-126.

Sharma, Bharat R ;Upali Amarasinghe and Cai Xueliang (2009) *Assessing and Improving Water Productivity in Conservation Agriculture Systems in the Indus-Gangetic Basin.* Lead paper at 4th World Congress on Conservation Agriculture (Session 1.4: Irrigated Systems), 4-7 February 2009, National Academy of Agricultural Sciences (India), NASC Complex. Pusa, New Delhi, India.

Sharma, B.R., G. Ambili. 2009. *Impact of climate change on water resources and potential adaptations for agriculture in the Indus-Gangetic basin*. Paper presented at the ICID/5th Asia Regional Conference, New Delhi, India, 6-11 December, 2009.

Sharma, Bharat R; Cai Xueliang. 2009. *Water saving technologies for rice-wheat systems in Indo-Gangetic Basin: New Developments.* Invited paper at the 15th Regional Technical Coordination Committee Meeting of the Rice-Wheat Consortium, 2-3 February, 2009; NASC Complex, New Delhi, India.

Cai, X.L.; Sharma, B.R. 2010. An assessment of agricultural water productivity in the Indo-Gangetic river basin: Current status and scope for improvement. Accepted paper for EWRI-India 2010 Conference on Water Management for Food Security and Sustainable Rural Development, 05-07 January, 2010, Indian Institute of Technology, Chennai, India.

Sharma, Bharat R ; Devaraj deCondappa. 2010. Impact of climate change on glacier and ice melt contribution towards the stream flows of the Indus and Ganges Rivers in South Asia. Paper submitted for Hydrology Conference 2010: The Changing Physical and Social Environment: Hydrologic Impacts and Feedbacks, October 11-13, 2010, san Diego, CA, USA.

(c)Project reports/Working papers

Bharat R Sharma, Upali A Amarasinghe, Alok Sikka (2008). *Indo-Gangetic River Basins: Summary Situation Analysis.* Project report.

Dhruba Pant (2009). *Irrigation and tenancy in Nepali agriculture: A rapid appraisal in three districts*. Draft Project Report.

Hosterman, H R., PG McCornick, EJ Kistin, A.Pant, B R Sharma, L. Bharati. 2009. Water and climate change adaptation: Focus on the Ganges- Brahmaputra river system. Duke University. IWMI Working Paper (09-03), 34 pp. Available at: www.nicholas.duke.edu/institute/ni.wp.09.03.pdf de Coiidappa, D„ L. Bharati, B.R. Sharma.2009. *Assessment and planning of water resources of the Indo-Ganges with Water Evaluation and Planning (WEAP) model: Current situation and possible scenarios*. IWMI Research Report (in progress).

Dhruba Pant, 2009. *Micro Irrigation Technology and its Potential to Meet the Productive and Consumptive Water Needs for Livelihood Improvement in Nepal Hills.* Draft project report.

Xueliang Cai, Bharat R. Sharma, Matin Mir Abdul, Devesh Sharma, Gunasinghe Sarath. 2009. *An assessment of agricultural water productivity in the Indo-Gangetic River basin: Current status and scope for improvement*. IWMI Research Report (Draft).

X. Stefanos, U. Amarasinghe. 2009. *Nexus of Water, Land and Poverty – Lessons from Case Studies in India, Pakistan and Nepal.* IWMI Research Report (Draft).

M. Golam Mustafa, Susana Hervas, Md. Giasuddin Khan, Bharat R. Sharma and M. Mokhlesur Rahman. 2010. *Assessing potential interventions to maximize fisheries - water productivity in the Eastern Gangetic Basin (EGB), Evaluation of Constraints and opportunities for Improvement: context Gorai-Madhumati (GM) sub-basin*; WorldFish-IWMI Research Report, Draft under Peer Review.

Upali A. Amarasinghe, R. Sirinivasulu , Madar Samad. 2009. *Water-Land-Poverty Nexus in the Indo- Gangetic Basin: A Synthesis*. Draft project report.

X. Stefanos. 2009.*Welfare and Water Use in Less Developed Regions of Ganges Basin (Bihar)*. Draft project report.

De Silva, S., A. Mukherji. 2009. *An inventory of national, sub-national and trans-boundary water-related legal instruments in the IG basin countries.* Draft project report and an electronic version (under development).

6.4. Research briefs

Water-Land-Poverty Nexus in the Indus-Gangetic Basin.

Water resources of Indus-Gangetic basin: Continuing threats and emerging challenges.

Where the Potential Lies? Disparities in Water Productivity across Indus-Gangetic Basin.

Policy and Institutions Analysis for the Indus-Gangetic Basin.

Investing on Interventions for Water Productivity improvement: A poverty reduction strategy in Indus-Gangetic Basin.

Fisheries Water Productivity in Eastern Indus-Gangetic Basin: Constraints and Opportunities for Improvement.

BIBLIOGRAPHY

Ahmad , M.D.; Turral, H.; Nazeer, A. 2009. Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan. *Agricultural Water Management* 96(2009): 551-564.

Ahmad, M. D., Turral, H., Masih, I., Giordano, M. and Mazood, Z. 2007. Water saving technologies: Myths and realities revealed in Pakistan's rive-wheat systems. *IWMI Research Report 108*, Colombo, Sri Lanka: International Water Management Institute.

Amarasinghe, U.; Sharma, B.R.; Aloysius, N.; Scott, C.; Smakhtin, V.; de Fraiture, C. 2005. Spatial variation in water supply and demand across river basins in India. Research report 83. Colombo, Sri Lanka: International Water Management Institute.

Amarasinghe, U.; Shah, T.; Turral, H.; Anand, B.K. 2007. India's water future to 2025-2050: business as usual scenario and deviations. Colombo, Sri Lanka, International Water Management Institute. 47 p. (IWMI Research Report 123).

Amarasinghe, U.; Shah, T.; Singh, O.P. 2008. Changing consumption patterns: implications on food and water dcemand in India. Colombo, sri Lanka, International Water Management Institute (IWMI Research Report 119). 43 p.

BBS (Bangladesh Bureau of Statistics) 2002: *Report of Poverty Monitoring Survey*, Ministry of Planning, Dhaka.

Biswas, B., D.C. Ghosh, M.K. Dasgupta, N. Trivedi, J. Timsina and A. Dobermann (2006)Integrated assessment of cropping systems in the eastern Indo-Gangetic plain, *Field Crops Research 99, 35–47*.

Cai, X.L.; Sharma, B.R.2009.Remote sensing and census based assessment and scope for improvement of rice and wheat water productivity in the Indo□Gangetic Basin. *Science in China Series E: Technological Sciences (ISI)*; 52(11):3300□3308

Cai, X.L*.,* Sharma, B.R*., 2010.* Integrating remote sensing, census and weather data for an assessment of rice yield, water consumption and water productivity in the Indo□Gangetic river basin. *Agricultural Water Management (ISI), 97(2): 309□316*

Christensen, J. H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W. T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. G., Räisänen, J., Rinke, A., Sarr, A. & Whetton, P. (2007). Regional climate projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller (Eds.), *The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change* (Volume , pp. 847-940). University Press.

Deaton, A. 2003b. Regional Poverty estimates for India, 1999-2000. New Jersey, U.S.A: Princeton University

Erenstein, O., R. K. Malik, and S, Singh. 2007. Adoption and Impacts of Zero-Tillage in the Rice-Wheat Zone of Irrigated Haryana, India. New Delhi: CIMMYT and the Rice-Wheat Consortium for the Indo-Gangetic Plains.

Erenstein, O., U. Farooq, R.K. Malik, and S. Muhammad (2008) On-farm impacts of zero tillage wheat in South Asia's rice–wheat systems. *Field Crops Research 105, 240–252* GBD. 2006.

M.L. Jat , M.K. Gathala , J.K. Ladha , Y.S. Saharawat, A.S. Jat , Vipin Kumar , S.K. Sharma ,V. Kumar , Raj Gupta .2009. Evaluation of precision land leveling and double zero-till systems in the rice–wheat rotation: Water use, productivity, profitability and soil physical properties. Soil & Tillage Research 105 (2009) 112–121

Hobbs, P. P. and Gupta, R. K. 2003. Rice-Wheat cropping systems in the Indo-Gangetic plains: Issues of water productivity in relation to new resource conserving technologies. In

Water productivity in agriculture: Limits and opportunities for improvement, ed. Kijne, J. W., Barker, R. and Molden, D, 239-253: CAB International, UK.

Jehangir, W. A., I. Masih, S. Ahmed, M. A. Gill, M. Ahmad, R. A. Mann, M. R. Chaudhary, A. S. Qureshi, H. Turral. 2007. Sustaining crop water productivity in rice-wheat systems of South Asia: A case study from the Punjab, Pakistan. *IWMI Working Paper 115*, Colombo, Sri Lanka: International Water Management Institute.

Hosterman, H.R; McCornick, P.G.; Kistin,E.J.; Pant, A.; Sharma, B.R.; Luna, B. 2009. *Water, climate change, and adaptation: Focus on the Ganges river basin.* Durham, NC, USA: Duke University,Nicholas Institute for Environment Policy Solutions. NI Working Paper. 34 pp.

Jain, S.K.; Agarwal, P.K.; Singh, V.P. 2007. Hydrology and Water Resources of India. Springer, the Netherlands. 1262 pp.

Mikhail, M; Yoder, R. 2009. Multiple- use water sevice implementation in Nepal and India: experiences and lessons for scale-up. International Development Enterprioses/ Challenge Program on Water and Food/ International water Management Institute, Colombo, Sri Lanka. Pp. 345.

Mukherji, A (2006), 'Political ecology of groundwater: The contrasting case of water abundant West Bengal and water scarce Gujarat, India', *Hydrogeology Journal* 14(3): 392-406.

Mukherji, A. (2007a), 'The energy-irrigation nexus and its implications for groundwater markets in eastern Indo-Gangetic basin: Evidence from West Bengal, India', *Energy Policy*, 35(12): 6413-6430.

Mukherji, A.; Villholth, K.G.; Sharma, B.R.; Wang, J.2009. Groundwater Governance in the Indo□Gangetic and Yellow River Basins: Realities and Challenges. London,U.K.: CRC Press. 325 pp (Hardbound) (*IAH Selected Papers on Hydrogeology 15)*

Mukherji, A.; Das, B.; Majumdar, N.; Nayak, N.C.; Sethi, R.R.; Sharma, B.R.2009. Metering of agricultural power supply in West Bengal, India: Who gains and who loses? *Energy Policy* (ISI), 37(12):5530□5539.

Repetto, R. 1994. *The "second India" revisited: population, poverty, and environmental stress over two decades*. Washington, DC, World Resources Institute.

Rodell,M.; Velicogna, I.; Famiglietti, J.S. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460, 999-1002 (20 August 2009) | doi:10.1038/nature08238

Saaty, T.L. (1980) The Analytic Hierarchy Process, McGraw-Hill, Inc., New York**.**

Scott, C; Sharma, B.R.2009.Energy supply and the expansion of groundwater irrigation in the Indus□Gangetic Basin*. International Journal of River Basin Management (*ISI), 7(2):119□124

Shah, T. 2009. Taming the Anarchy: Groundwater Governance in South Asia. Washington, D.C., RFF Press. 305 pp.

Shah, T. ; Mehmood, U.; Zubair, M.K.; Banerjee, P.S.; Singh, O.P.; Rehman, S.U. 2009. Is irrigation water really free?: A reality check. *World Development*, 37: 422-434.

Sharma, B.R.; Amarasinghe, U.A.; Sikka, A. 2008. Indo-Gangetic River Basins: Summary situation anaslysis, Basin Focal Projects- Challenge Program on water and Food, Colombo, Sri Lanka, 14 pp.

Sharma, B.R.; Riaz, M.V.; pant, D.; adhikary, D.L.; Bhatt, B.P.; Rahman, H. 2010. Water poverty in the northeastern hill region (India): potential alleviation through multiple- use water systems- cross-cutting learning from Nepal hills. New Delhi, India, International water Management Institute (IWMI-NAIP Report 1), 44 p.

Sharma, Bharat R; Peter G McCornick.2006. Domestic policy framework on adaptation to climate change in water resources: Case study for India. (Commissioned Paper). Proceedings *“Working Together to Respond to Climate Change” Annex I Expert Group Seminar of OECD Global Forum on Sustainable Development*, Paris, France. 25 pages (available at www.oecd.org)

WBSEB (2006), West Bengal State Electricity Board Yearbook, Kolkata, India

WIDD (2004). Groundwater Resources of West Bengal: An Estimation by GEC-1997 Methodology. Water Investigation and Development Department (WIDD), Kolkata, Govt. of West Bengal.

PROJECT PARTICIPANTS

Dr. Bharat Sharma, Project Leader; Senior Researcher-I & Head, International Water Management Institute (IWMI), New Delhi Office, NASC Complex, CG Block, Pusa, New Delhi-110012, India (b.sharma@cgiar.org)

Dr. Peter Gordon McCornick. Project Leader (upto March, 2009), presently at Duke University, Durham. NC, USA

Dr. Vladimir Smakhtin, Theme Leader-I, IWMI, Colombo. Sri Lanka

Dr. Tushaar Shah, Senior Fellow, IWMI-Anand, India

Dr. Madar Samad, Regional Director, IWMI-South Asia, Hyderabad, India

Dr. Alok K Sikka, Technical Expert (Watershed Development), National Rainfed Area Authority (NRAA), New Delhi.

Dr. Upali Amarasinghe, Senior Researcher, IWMI, New Delhi, India.

Dr. RPS Malik, Senior Researcher, IWMI, New Delhi, India.

Dr. Stefanos Xenarios, Post Doctoral Fellow, IWMI, New Delhi, India.

Dr. Luna Bharati, Researcher, IWMI, Nepal office, Kathmandu, Nepal.

Dr. Dhruba Pant, Head, IWMI, Nepal office ,Kathmandu, Nepal.

Dr. Devaraj de Condappa, SEI Associate, Stockholm Environment Institute, Puducherry, India.

Dr. M D Ahmad, Senior Researcher, IWMI, Colombo. Sri Lanka (now at CSIRO, Australia)

Dr. Cai Xueliang, Post Doctoral Fellow, IWMI, Colombo, Sri Lanka.

Dr. Asad Sarwar Qureshi, Water Resources Management Specialist, IWMI, Pakistan.

Mr. Abdul Hakeem Khan, Researcher, , IWMI, Lahore, Pakistan.

Mr. Waqas Ahmed, Junior Research Officer, IWMI, Pakistan.

Dr. Aditi Mukherji, Researcher, IWMI, Colombo, Sri Lanka.

Mr. Mir Matin, IDIS Manager, IWMI, Colombo, Sri Lanka.

Dr. M A Khan, Director, ICAR-RCER, Patna, India

Dr. Atul K Singh, ICAR-RCER, Patna, India

Ms. Ambili G K, Project Associate, IWMI, New Delhi.

Dr. Mohammad Ahmad, University of Queensland, Australia (on sabbatical leave to IWMI, New Delhi for six months).

Dr. William Collis/ Dr. Alan Brooks, Director, Worldfish Center, Dhaka, Bangladesh.

Dr. Mohammad Giasuddin Khan, , Worldfish Center, Dhaka, Bangladesh.

Mohammad Golam Mustafa, Worldfish Center, Dhaka, Bangladesh.

Susana Hervas Avila, Intern, Worldfish Center, Dhaka, Bangladesh.

Mr. Mokhlesur Rahman, Centre for Natural Resources Science, Dhaka, Bangladesh

Mr. R Indu, INREM Foundation, Anand, India

Administrative Support

Ms. Mala Ranawake, Administrative Officer, IWMI, Colombo, Sri Lanka.
Mr. N. Aakanksh, Administrative Officer, IWMI, New Delhi, India.
Ms. Navanita Rani, Administrative Officer, IWMI, Hyderabad, India

APPENDIX: ABSTRACTS OF SOME KEY PUBLICATIONS.

***Intl. J. River Basin Management* Vol. 7, No. 1 (2009), pp. 1–6**

© 2009 IAHR, INBO & IAHS

Energy supply and the expansion of groundwater irrigation in the Indus-Ganges Basin

CHRISTOPHER A. SCOTT, *Asst. Professor, Department of Geography & Regional Development, and Udall Center for Studies in*
Public Policy, University of Arizona, Tucson, Arizona 85721, USA. Email: cascott@email.arizona.edu
BHARAT SHARMA, *Senior Researcher, International Water Management Institute, New Delhi, India. Email: b.sharma@cgiar.org*

ABSTRACT

Irrigation using groundwater has expanded rapidly in South Asia since the inception of the Green Revolution in the 1970s. Groundwater currently represents the largest source of irrigation in the Indus-Ganges Basin (IGB), which feeds over one billion people and provides direct livelihoods for hundreds of millions of farmers. Although abundant in absolute terms, groundwater is overexploited in the western IGB plains and is underutilized in the east. The spatial and temporal patterns of groundwater development are the result of multiple demand factors: (a) farmer investment, (b) subsidies and markets, and (c) population density; as well as supply factors: (d) sources of groundwater recharge, and (e) energy supply and pricing. This paper examines trends in electricity supply and groundwater development in the Indian portion of the IGB over the 1980 – 1999 period, with contextual reference to groundwater irrigation in Pakistan, Nepal, and Bangladesh. Principal findings include early-1980s' growth in numbers of electric pumps across the Indian IGB followed by 1990s' stagnation in the eastern part of the basin; this trend is linked to electricity supply and pricing policies, which have varied markedly from state to state. The eastern IGB presents an energy-groundwater paradox: a region rich in energy sources but with inadequate electricity supply that has led to increased reliance on diesel power, which in turn is limiting development of groundwater – one of this region's most abundant and agriculturally productive resources.

Water Resource Management
DOI 10.1007/s11269-009-9513-3 (Springer Science)

Challenges and Prospects of Sustainable Groundwater Management in the Indus Basin, Pakistan

Asad Sarwar Qureshi , IWMI-Office, Lahore, Pakistan
e-mail: a.sarwar@cgiar.org
Peter G. McCornick IWMI, Colombo, Sri Lanka
e-mail: p.mccornick@cgiar.org
A. **Sarwar**, Punjab Agricultural Department, On-Farm Water Management, Lahore, Pakistan
e-mail**:** asrarsarwar@gmail.com
Bharat R. Sharma, IWMI-Office, New Delhi, India
e-mail: b.sharma@cgiar.org

ABSTRACT

In Pakistan, on-demand availability of groundwater has transformed the concept of low and uncertain crop yields into more assured crop production. Increased crop yields has resulted in food security and improved rural livelihoods. However, this growth has also led to problems of overdraft, falling water tables and degradation of groundwater quality, and yields generally remain well below potential levels. Over the last three decades, Pakistan has tried several direct and indirect management strategies for groundwater management. However the success has been limited. This paper argues that techno-institutional approaches such as introducing water rights, direct or indirect pricing and permit systems are fraught with difficulties in Pakistan due to its high population density and multitude of tiny users. Therefore there is a need to develop frameworks and management tools that are best suited to Pakistani needs. Pakistan should follow both supply and demand management approaches. For demand management, adoption of water conservation technologies, revision of existing cropping patterns and exploration of alternate water resources should be encouraged. For supply management, implementation of the groundwater regulatory frameworks developed by Provincial Irrigation and Drainage Authorities (PIDAs) and introduction of institutional reforms to enhance effective coordination between different organizations responsible for the management of groundwater resources should be given priority.

Proceedings 2: International Forum on Water and Food, (Volume-III), Addis Ababa, November 10- 14, 2008, CPWF, Colombo.

Evolution of Managing Water for Agriculture in the Indus River Basin

Abdul Hakeem Khan1, Peter McCornick and Asim Rauf Khan
1International Water Management Institute (IWMI) Lahore, Pakistan, a.khan@cgiar.org

ABSTRACT

The weir controlled irrigation system development of the Indus Basin started in the mid 19th century and has limited capacity for further development now. Groundwater has also been developed and even over-exploited in many parts despite having quality (salinity) problems. However, the management of surface water is weak, lacking transparency and accountability, leading to inequitable and unreliable supplies in the lower reaches of the system, while there is no rule or control over groundwater use. The cropped area and production of major crops has increased greatly but both land as well as water productivity is much lower than potential. Improved and innovative management techniques and technologies should be employed at all levels to meet the food requirements of the increasing population and supporting the 70 per cent of the population dependent on rural livelihoods, and the national economy.

Agricultural Water Management 97 (2010) 309–316 (Elsevier)

Integrating remote sensing, census and weather data for an assessment of rice yield, water consumption and water productivity in the Indo-Gangetic river basin

X.L. Cai, International Water Management Institute, 127 Sunil Mawatha, Pelawatta, Battramulla, Sri Lanka
B.R. Sharma International Water Management Institute, Delhi Office, NASC Complex, CG Block, Dev Prakash Shastri Marg, Pusa, New Delhi 110012, India

ABSTRACT

Crop consumptive water use and productivity are key elements to understand basin water management performance. This article presents a simplified approach to map rice (Oryza sativa L.) water consumption, yield, and water productivity (WP) in the Indo-Gangetic Basin (IGB) by combining remotely sensed imagery, national census and meteorological data. The statistical rice cropped area and production data were synthesized to calculate district-level land productivity, which is then further extrapolated to pixel-level values using MODIS NDVI product based on a crop dominance map. The water consumption by actual evapotranspiration is estimated with Simplified Surface Energy Balance (SSEB) model taking meteorological data and MODIS land surface temperature products as inputs. WP maps are then generated by dividing the rice productivity map with the seasonal actual evapotranspiration (ET) map. The average rice yields for Pakistan, India, Nepal and Bangladesh in the basin are 2.60, 2.53, 3.54 and 2.75 tons/ha, respectively. The average rice ET is 416 mm, accounting for only 68.2% of potential ET. The average WP of rice is 0.74 kg/m3. The WP generally varies with the trends of yield variation. A comparative analysis of ET, yield, rainfall and WP maps indicates greater scope for improvement of the downstream areas of the Ganges basin. The method proposed is simple, with satisfactory accuracy, and can be easily applied elsewhere.

Agricultural Water Management Volume 96(4), April 2009: 551-564

Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan

M.D. Ahmad Formerly at International Water Management Institute (IWMI), Global Research Division, PO Box 2075, Colombo, Sri Lanka
H. Turral, CSIRO, Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia
A. Nazeer, International Water Management Institute (IWMI), Pakistan National Office, 12 km Multan Road, Lahore, Pakistan

ABSTRACT

Irrigation policy makers and managers need information on the irrigation performance and productivity of water at various scales to devise appropriate water management strategies, in particular considering dwindling water availability, further threats from climate change, and continually rising population and food demand. In practice it is often difficult to access sufficient water supply and use data to determine crop water consumption and irrigation performance. Energy balance techniques using remote sensing data have been developed by various researchers over the last 20 years, and can be used as a tool to directly estimate actual evapotranspiration, i.e., water consumption. This study demonstrates how remote sensing-based estimates of water consumption and water stress combined with secondary agricultural production data can provide better estimates of irrigation performance, including water productivity, at a variety of scales than alternative options. A principle benefit of the described approach is that it allows identification of areas where agricultural performance is less than potential, thereby providing insights into where and how irrigation systems can be managed to improve overall performance and increase water productivity in a sustainable manner. To demonstrate the advantages, the approach was applied in Rechna Doab irrigation system of Pakistan's Punjab Province. Remote sensing-based indicators reflecting equity, adequacy, reliability and water productivity were estimated. Inter- and intra-irrigation subdivision level variability in irrigation performance, associated factors and improvement possibilities are discussed.

Science in China Press/ Springer, Series E: Technological Sciences, 52(11):3300-3308

Remote sensing and census based assessment and scope for improvement of rice and wheat water productivity in the Indo-Gangetic Basin

CAI XueLiang, International Water Management Institute (IWMI), 127 Sunil MW, Pellawatta, Battramulla, Sri Lanka;
SHARMA Bharat, International Water Management Institute (IWMI), New Delhi Office, NASC Complex, CG Block, Dev Prakash Shastri Marg, Pusa, New Delhi 110012, India

ABSTRACT

Understanding of crop water productivity (WP) over large scale, e.g., river basin, has significant implications for sustainable basin development planning. This paper presents a simplified approach to combine remote sensing, census and weather data to analyze basin rice and wheat WP in In-do-Gangetic River Basin, South Asia. A crop dominance map is synthesized from ground truth data and three existing LULC maps. National statistics on crop area and production information are collected and the yield is interpolated to pixel level using moderate resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI). Crop evapotranspiration is mapped using simplified surface energy balance (SSEB) model with MODIS land surface temperature products and meteorological data collected from 56 weather stations. The average ET by rice and wheat is 368 mm and 210 mm respectively, accounting for only 69% and 65% of potential ET, and 67% and 338% of rain-fall of the crop growth period measured from Tropical Rainfall Measurement Mission (TRMM). Average WP for rice and wheat is 0.84 and 1.36 kg/m3 respectively. WP variability generally follows the same trend as shown by crop yield disregarding climate and topography changes. Sum of rice-wheat water productivity, however, exhibits different variability leading to better understanding of irrigation water management as wheat heavily relies on irrigation. Causes for variations and scope for improvement are also analyzed.

World Development Volume 37(2), February 2009: 422-434

Is Irrigation Water Free? A Reality Check in the Indo-Gangetic Basin

Tushaar Shah, International Water Management Institute, Gujarat, India
Mehmood Ul Hassan, International Water Management Institute, Lahore, Pakistan
Muhammad Zubair Khattak, Peshawar University of Agriculture, Peshawar, Pakistan
Parth Sarthi Banerjee Centre for Studies in Social Sciences, Kolkatta, India
O.P. Singh, Banaras Hindu University, Varanasi, India
Saeed Ur Rehman, Pakistan Rural Institutional and Management organization for Economic Development, Khanewal, Pakistan

ABSTRACT

"Getting prices right" is the silver bullet widely advocated to developing countries in fighting waste, misallocation and scarcity of water. In the vast, poverty-stricken Indo-Gangetic basin, however, high surrogate water price is driving out small-holder irrigation. With rising diesel prices, most small-holders who use borewells for irrigation find effective water use cost soaring, obliging them to economize on water use even by quitting irrigated farming. Electrified borewell owners, far fewer, face low marginal cost but have to contend with stringent electricity rationing. Public irrigation systems grossly under-price irrigation, but these are getting marginalized despite massive government and donor investments.